Environmental Research Institute
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Assessing Energy Security & Macroeconomic feedback in National and Global Integrated Energy Systems Models

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Thesis submitted for the degree of Doctor of Philosophy to
The National University of Ireland, Cork

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

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December 2015

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DECLARATION

I hereby declare that this thesis is my own work and that is has not been submitted for another degree, either at University College Cork or elsewhere. Where other sources of information have been used, they have been acknowledged.

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ACKNOWLEDGEMENTS

Brian, thank you for all the opportunities, doors opened, and collaborators introduced, travel encouraged, protection provided, and the yogi mentality with which you do not micromanage our energy policy and modelling group. Hannah, thanks for the welcome, and help settling in the early days, the friendship and boat trips in the later. Fionn, Paul, and Denis, thanks for being great colleagues and collaborators, the differences you each bring to the ERI table, the chats, the laughs, the sushi, the Kerry wit, the music, the recommended reading, the travel advice, sharing the ups, and the downs. Thanks for new ideas and methods from Eamonn, Séan, Clare, Tomás, Jason and Kathleen, the EPMG is in good hands. Tony thank you for the opportunity to work in the HMRC and GREP. Thank you for the parting words.

Thank you Socrates for the interest taken in my research, and your insights providing clarity on fledgling ideas. Antti, thanks for the being the mine of information on GAMS and TIMES programming. Ale and Mauri, thanks for the TIMES training in the early days and for the continued development and collaboration. Thanks for hosting me in Torino, and for the carpaccio. Thank you George, Giancarlo, Maryse, Amit, and the ETSAP community at large for the interesting and generally fruitful workshops.

Thanks to Alan, Jerry and Sarah in the Environmental Research Institute for providing excellent facilities and to Paul and Helen for keeping her afloat. Thank you to Ray and Cora in Beaufort for the funding arrangements, and managing financial matters. Thank you to the Higher Education Authority for funding under the Graduate Research Engineering Programme in Energy (GREP). Thank you to anonymous reviewers for constructive criticism and suggestions, as well as Tom, Clare and Fionn for reviewing this thesis.

Thank you Trish.

Thank you Mom. Thank you Dad.

Thank you Isolde my love.

Executive Summary

Ireland imports 88% of its energy requirements. Oil makes up 59% of total final energy consumption (TFC). Import dependency, low fuel diversity and volatile prices leave Ireland vulnerable in terms of energy security. The Supply/Demand Index, developed by the energy research centre of the Netherlands (ECN), has been used previously as a metric to assess Irish energy security. The method assesses both supply and demand side quantitative factors by sector, assigns expert opinion weights to these factors to allocate risk, and give a relative picture of energy security when compared to EU benchmarks. The thesis further develops this index in order to address a number of limitations and to develop further insights into energy security. Firstly, the update develops a time series dataset taking into account the most recent Irish Energy balance data from the International Energy Agency (IEA) and EUROSTAT, while economic-energy indicators are supplemented from the ODYSSEE database. Secondly, given Irelands reliance on the UK for the primary energy supply for refined oil products and natural gas, an appropriate restructuring of Irish primary energy supply risk is developed to account for the risk in UK chain of primary energy supply. This is deemed necessary given the shift in UK energy balance from net exporter to net importer of energy.

Moving from energy index analysis to energy systems analysis, this thesis develops the first energy security scenarios for Ireland to 2050 using long term macroeconomic forecasts to 2050, with oil production and price scenarios from the International Monetary Fund (IMF), soft-linked to the Irish-TIMES energy systems model. The analysis focuses on developing a least cost optimum energy system for Ireland under scenarios of constrained oil supply from 2012 (0.8% annual import growth, and –2% annual import decline) and subsequent sustained long term price shocks to oil and gas imports. The results point to gas becoming the dominant fuel source for Ireland, at 54% total final energy consumption in 2020, supplanting oil from reference projections of 57% to 10.8% TFC. In 2012, the cost of net oil imports stood at €3.6 billion (2.26% GDP). The modelled high oil and gas price scenarios show an additional annual cost in comparison to a reference of between €2.9bn and €7.5bn by 2020 (1.9% - 4.9% of GDP) to choose to develop a least cost energy system. Investment and ramifications for Irish energy security are discussed.

In a climate constrained future, hybrid energy-economy model coupling gives additional insight into interregional competition, trade, industrial delocalisation and overall macroeconomic consequences of decarbonising the energy system. Decarbonising the energy system is critical in mitigating climate change. This thesis summarises modelling methodologies developed in the International Energy Agency Energy Technology Systems Analysis Programme (IEA-ETSAP) community to assess economic impacts of decarbonising energy systems at global and national levels. The range of economic impacts is regionally dependent upon the stage of economic development, the level of industrialisation, energy intensity of exports, and competition effects due to rates of relative decarbonisation. Decarbonisation targets of developed nations are estimated to result in a manageable GDP loss in the region of 2% by 2050. Energy intensive export driven developing countries, such as China and India, and fossil fuel exporting nations can expect significantly higher GDP loss of up to 5% GDP by 2050. The approaches outlined within have guided the first evidence based decarbonisation legislation and continue to provide additional insights as increased sectoral disaggregation in hybrid modelling approaches is achieved.

This thesis develops a general equilibrium feedback in technology rich integrated energy systems modes to equitable burden sharing rules for climate change mitigation at an Irish and Global scale. The IEA-ETSAP hybrid global Integrated Assessment Model TIAM-MACRO is used to investigate the efficient bottom-up energy system required to meet a 2°C limit target with 66% probability while optimising for consumer welfare. Least cost efficient 2°C scenario (2DS) emissions are compared alongside burden sharing rules, including contract and convergence equalisation of emissions per capita, equalisation of regional GDP loss, compensation for energy cost increases in Least Developed Countries (LDCs), full compensation for GDP loss in LDCs and two interpretations of the “Brazil Proposal” of historical cumulative responsibility for temperature forcing.

The results in this thesis for equal future emissions per capita challenge statements that this approach will aid emerging economies, mainly China and India. This thesis shows that China, India and developing Asia suffer increased economic losses using equal per capita burden sharing rules in comparison to the efficient least cost scenario. China fares best when the burden sharing rules focus on equalisation for economic losses, while India, Other Developing Asia, and Africa have greater economic benefits when rules focus on equitable cumulative emissions per capita. Finally this approach can quantify the levels of capital transfer the Green Climate Fund should manage going forward, indicates which regions should pay, which regions should receive, and quantify the amount of capital transfers.

Thesis Outputs

Journal Papers

Glynn, J., Chiodi, A., Gargiulo, M., Deane, J.P., Bazilian, M., Gallachóir, B.Ó., 2014. Energy Security Analysis: The case of constrained oil supply for Ireland. Energy Policy 66, 312–325. doi:10.1016/j.enpol.2013.11.043

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Glynn, J. – Invited Panellist - Department of Communications, Energy and Natural Resources Seminar – Priority 4 – Ensuring a balanced and Secure Energy Mix, Chester Beatty Theatre, 11 11 2014

Glynn, J. – Invited Participant – Royal Irish Academy Climate Change Masterclass with Professor Chris Field. 28 October 2014 Royal Irish Academy, Dublin, Ireland.

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Units and Abbreviations

1.5DS	1.5 degree scenario
2DS	2 degree scenario
AEEI	Autonomous Energy Efficiency Index
AEEIF	Autonomous Energy Efficiency improvement factors
AESC	Annual Energy System Costs
AFR	Africa
AIM	Asian-Pacific Integrated Assessment Model
AUS	Australia
BASE	Baseline
BAU	Business as usual
BER	Building Energy Rating
BESOM	Brookhaven Energy System Optimisation Model
BGE	Bord Gáis Eireann
BP	British Petroleum
BRENT	Brent (EU Crude Oil Benchmark)
BU	Bottom Up
C&T	Conversion and Transmission
CAN	Canada
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CDIAC	Carbon Dioxide Information Analysis Center
CER	Commission for Energy Regulation
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
CH4	Methane
CHI	China
CHP	Combined Heat and Power
CIEP	Clingendael International Energy Programme
CMP	Common measuring points
CNG	Compressed Natural Gas
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
COSMO	Irish Macroeconomic model
CSA	Central South America
CSO	Central Statistics Office
ddf	demand decoupling factors
DDR	Demand Drivers
DECC	UK Department of Energy and Climate Change
DSGE	Dynamic Stochastic General Equilibrium
DUKES	Digest of United Kingdome Energy Statistics
e_SAGE	South Africa General Equilibrium model
ECN	Energy Research Centre of the Netherlands
ED	Elastic Demand

EEU	Eastern Europe
EIA	Energy Information Office
EIRGRID	The Irish electrical Transmission System Operator
EMEC	Environmental Medium Term Economic Model (Sweden)
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
EPMG	Energy Policy and Modelling Group
ESD	Energy Service Demands
ESRI	Economic and Social Research Institute
ETP	Energy Technology Perspectives
ETS	Emissions Trading Scheme
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
EUROSTAT	European Statistical Body
EWIC	East West Interconnector
FFI	Fossil Fuel and Industry
FSU	Former Soviet Union
GAMS	General Algebraic Modelling Software
GCP	Global Carbon Project
GDP	Gross Domestic Product
GE	General Equilibrium
GEM-E3	A General Equilibrium Model
GHG	Green House Gases
GIMF	Global Integrated Monetary and Fiscal Model
GNI	Gas Networks Ireland
GNP	Gross National Product
GTAP	Global Trade Analysis Project
GVA	Gross Value Added
GW	Gigawatt
GWh	Gigawatt hour
HERMES	Irish Demographic Macro economic model
IAM	Integrated Assessment Model
IEA	International Energy Agency
IMF	International Monetary Fund
IND	India
IPCC	Intergovernmental Panel on Climate Change
JPN	Japan
kb/d	thousands Barrels of Oil per day
kt	Kilo tonnes
ktoe	thousands tonnes of oil equivalent
kWh	Kilowatt hour
LDC	Least Developed Countries
LEAP	Long-range energy alternatives planning system
LP	Linear Programme/Programming
LTMS	Long term mitigation scenarios

MARKAL	Market Allocation
MEA	Middle East
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MEX	Mexico
MJ	Megajoules
MM	MARKAL MACRO
Mpkm	million passenger kilometres
Mt	Megatonnes
Mtkm	Million tonne kilometres of freight
Mtoe	million tonnes of oil equivalent
N20	Nitrous Oxide
NEEAP	National Energy Efficiency Action Plan
NETS	Non-Emissions Trading Scheme
NIER	National Institute for Economic Research (Sweden)
NLP	Non Linear Programme/Programming
NO	Norway
Nox	Nitrogen Monoxide
NREAP	National Renewable Energy Action Plan
NTX(nmr)	Export Trade of Numeraire Good
ODA	Other Developing Asia
PE	Partial Equilibrium
PES	Primary Energy Supply
PET36	Pan European TIMES
PJ	Petajoules
POA	Post optimisation analysis / algorithm
PPP	Polluter Pays Principle
QSF	Quadratic Supply Functions
REF	Reference
RES	Reference Energy System
RES-E	Renewable Energy Target - Electricity
RES-H	Renewable Energy Target - Heat
RES-T	Renewable Energy Target - Transport
ROI	Republic of Ireland
S/D	Supply Demand Index
SAM	Social Accounting Matrix
SATIM	South Africa TIMES model
SCGE	Spatial General Equilibrium Model
SEAI	Sustainable Energy Authority of Ireland
SEC	Specific Energy Consumption
SEM	Single electricity market
SKI	South Korea
SONI	System Operator of Northern Ireland
SoS	Security of Supply
SSP	Shared Socioeconomic Pathways

TD	Top down
TFC	Total Final Consumption
TIAM	the TIMES Integrated Assessment
TIMES	The Integrated MARKAL-EFORM System
tkm	Tonne-Kilometre
TM	TIMES MACRO
TMSA	TIMES MACRO Stand Alone
toe	tonne of oil equivalent
TPER	Total Primary Energy Requirement
TSO	Transmissions System Operator
TW	Terawatt
UCC	University College Cork
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
vkm	Vehicle Kilometres
WEU	Western Europe
WTI	West Texas Intermediate (US Crude Oil Benchmark)

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Chapter 1 INTRODUCTION

1.1 BACKGROUND

This thesis describes in detail energy systems modelling methodologies on Irish and global scales based on accepted rules of economic theory, assumed behaviour traits and trade, Climate science, environmental economics, and engineering energy systems modelling methods. This research posits that climate change is a commons problem of interregional and intertemporal inequity between free riders who have dumped waste gases into the global atmospheric commons, benefiting from carbon intensive development, and those who will face damage costs they did not, do not, and are unlikely to create in the future.

The specific introductions of relevant energy security and climate science background information are introduced in each chapter as appropriate and as per their respective papers.

The study of energy security and equitable distribution of financial impacts of technological mitigation of climate change, are elements of the same types of energy market externalities, albeit at differing scales and levels of system integration. This thesis will outline an evolution of thought from singular energy security risks, such as the economically-naive concept of peak oil, to an integrated, equitable and decarbonised global energy system. In understanding security, it is appropriate to begin with a background introduction about why nations fail to develop robust and secure institutions, i.e. an outline of the institutional structures that foster and enable the energy insecurity and environmental risks we face today. Furthermore, it is necessary to understand the social capital and social norms potentially required to mitigate and adapt to climate change through global law and binding targets.

1.1.1 ECONOMIC HISTORY OF INSTITUTIONAL CAPITAL

The rule of law establishes the rules of a game of competition between anthropocentric androplutocrats, “the elite”, and the rest of society. The ruling classes have evolved from those holding a monopoly on the legitimate use of violence (Olson, 1993). Modern law functions with the presupposition of an altruistic righteousness to protect society from unethical behaviour and violence under the fear of mankind's history. In reality it seems to be the first line in a governance structure to enforce institutional control over personal rights, mobility, acceptable relationships, flow of information, property rights, trade frameworks, money creation, usury and the cognitive map of the zeitgeist; i.e. the way the public think and things that are publicly left unsaid. While communism attempts quite openly to control society with engineered deterministic rationality, capitalism attempts to control behaviour more covertly, where citizens are allowed to make their own decisions within legal behavioural limits. The rule of law legitimises violence towards nature, assumes dominion thereof, where dissection into units of property and commodities are required as the natural capital upon which productivity and economic growth depends.

In economic history the rule of law and the protection of property rights are deemed critical in long term development, growth maximisation, and the development of a prosperous nation (Acemoglu and Robinson, 2012; Olson, 2000). The accumulation of social capital to form revolutionary institutions, the scale of groups forming said institutions, the motivation of decision makers, their policy choices, their incentive structures, and regulatory oversight dictate the prosperity of a nation, within the level of stability and accountability that the rule of law enforces.

The rule of law itself does not ensure efficient allocation of resources, social optimum outcomes, nor prosperity. The rule of law ensures enactment of policies from the governing classes, be they elected inclusive democracies promoting creative destruction through the pluralistic dispersion of power or extractive sclerotic autocracies.

The example of roving or stationary banditry is typical of agrarian society where a region is subject to theft of produce. The unpredictable free-rider nature of roving bandits, disincentivise planning, investment or long term productive behaviour on the part of their victims, removing any benefit from production above subsistence rates. Roving banditry is seen as unsustainably extractive in that the total theft of a region's produce leaves little to be gained in returning for more theft. Stationary banditry on the other hand, differs primarily in the establishment in a rule of law in the simplest sense to ensure that the chief stationary bandit is the sole thief in the region. Thus through the protection and establishment of exclusion rights of the region from and to other bandits, the stationary bandit provides a social good of stability, enabling an increased level of production for his proportionate extraction. It is mutually beneficial and in both the stationary bandit and his subjects self-interest to increase regional stability and thus incentivise increased production for theft or taxation. This is seen as the first act of centralisation of power.

Monarchies with the “long live the king” mantra, continues the promotion of stability, ownership and mutual benefit in maximising the produce in a social contract. Maximum levels of income are only attained with high levels of investment, with lower discount rates and long term time horizons. An individual’s decision to invest is based upon gaining benefit from investment, which requires a stable long term horizon in which to accrue a benefit, assurances that the autocrat will not excessively extract taxes, that their right to private property is protected, that loans and contracts will be enforced, and debts will be honoured (Olson, 1993). However, destabilising expansive extractive policies, transitions in power or external events can tip the balance of power, causing collective action in revolutions and in some cases, critical junctures. COP21 may be one such critical juncture.

The bubonic plague killed half of the population of Europe, significantly reducing the labour force, tipping the balance of power of the feudal order into the hands of those who had been servile peasants. The coercive power of landowners was reduced, as they demanded scarce labour. In England this firstly resulted in the statute of labourers to limit claims to increased pay, but this statute was not enforced by law, and ultimately the increased inclusiveness and dispersion of power led to increased freedom from dues and fines. The continual struggle in the balance of power culminated in the English Civil war and finally the Glorious Revolution (1688). This brought about the dispersion of power, removing control from the monarchy to an inclusive parliament and the establishment of political and economic institutions that would shape who would gain from national prosperity, through the framework of incentives for trade and investment. This was the first creation of a pluralistic society, which accelerated the balance of power into centralised institutional governance, with rule of law, decreased individual autocratic extraction, enforcement of property rights, the introduction of patents for ideas and inventions, enforcement of contracts and honouring of debt, naval protection of mercantile shipping, the trend of increased education, innovation and technological advancement. The technological mechanisation and increased incentivisation of production lead to competitive advantages, infrastructure, innovation and increased prosperity in England.

Olson, and Ostrom formalise theories around action in the common interest, the balance of power, transaction costs, institutional capital, indigenous commons management, Coasian bargaining, externalities, rational optimum free riding behaviour, the prisoners dilemma, games without cores, selective incentives and rational ignorance of electorates, where the personal cost in understanding legislation can outweigh the benefit of effort to understand (Olson, 1993; Ostrom, 2000, 1990; Ostrom and Field, 1999). Ideally the rule of law protects electorates, where the group size has become too large to naturally act in the common interest or to negotiate coasian bargains, to mitigate market externalities and coercion. Democratic governing institutions find that providing a police force to enforce the rule of law results in a minimal cost, in comparison to the net increase in wealth and production provided by the stability that the police enforced rule of law enables. Once the rule of law is established and institutionally strong, the cost in opposing the institution becomes prohibitive, thereby reinforcing stability and reducing the probability of conflict and war.

The rule of law can be used extractively to cause inefficient outcomes even for resource rich nations; the Stalinist Soviet system is a case in point. Stalin used law to enforce policies which confiscated resources, assets and removing potential markets. Vast resources were mobilised that caused inefficient internal bureaucracies, bureaucratic competition and complex hierarchies with non-linearly incentivised manipulation of information proportional to the depth of hierarchy. Ultimately, this resulted in corruption and a sclerotic nation as the advantage of private innovation was not realised. Stalin could not analyse and control all information. Price control, market contrary manipulation, extractive policies, the speed of information and the lack of competition limit the efficient use of resources and promoted corruption. All watchers and collectors within the Stalinist system were incentivised to expropriate unnoticeable levies through conspiring in their own self-interest; this lead to the corruption, stagnation, and collapse of the Soviet Union.

The same fate may now await western capitalism where the balance of power has swung to corporate profit rather than the social good. The role played by the rule of law in money creation, currency debasement, debt enslavement and finally enforcing bank bailouts, shows the corrupting of law in the favour of core corporate and financial stability over public social stability. Similar protectionist behaviour brought about the fall of Venician prosperity, as with the Austro-Hungarian Empire (Acemoglu and Robinson, 2012). The historic effects of corruption in law and an accumulation of power maybe the clearest sign of the potential of the end of empire, with a social, resource, and environmental collapse underway.

1.1.2 Energy System Security is more complex than Peak Oil

Energy security has often been, and still is in certain circles, simplified into polarised arguments of access to fossil fuel resources. The geological perspective driven from within the oil industry originally coined the term “Peak Oil” (Campbell and Laherrère, 1998). Peak Oil, temporarily held research credence in the period of 1998 – 2009, especially during the period of 2003-2009 while global oil markets moved up the marginal supply cost curve driven by increased oil demand and conventional oil production began to slow (IEA, 2008, 1998). Peak Oil, which originally piqued interest in energy security, is overly simplified and ignores the economic complexities and uncertainties of supply side economics (McGlade, 2012). Taking into account reserve growth, enhanced oil recovery and disruptive technological innovation, there is more oil (as well as gas and coal) in current reserve estimates, above and beyond potentially ultimately recoverable resources, than the global atmospheric commons can sustainable absorb (Edenhofer et al., 2014; McGlade and Ekins, 2015, 2014).

1.1.3 CLIMATE CHANGE

The adoption of the Paris Agreement in December 2015 is a critical juncture in climate change policy, and global diplomacy. (IPCC. Conference of Parties (COP), 2015). 195 countries have agreed to a global limit of anthropogenic global warming to 2°C with an ambition to go as low as possible towards 1.5°C. Remaining Carbon Dioxide budgets to meet this decarbonisation mitigation target limits net emissions to no more than 1000GtCO_2e for a 66% probability of meeting 2°C, with 400GtCO_2e the remaining budget for a 66% probability of meeting the 1.5°C target (*Climate Change 2014: Synthesis Report. Contribution of Working Groups l, ll, lll to the fifth assessment report of the Intergovernmental Panel on Climate Change.*, 2014; Friedlingstein et al., 2014; Le Quéré et al., 2015). Figure 1.1 summarises the rate of historical and potential future emissions, as well as the time when global emissions budgets will be exhausted at current rates. Intended Nationally Determined Contributions (INDCs) to mitigation are recognised to only lead the world toward a 2.7°C – 3.4°C warming relative to post-industrial temperature levels (International Energy Agency, 2015; Olivier et al., 2015, p. 2). There is a significant level of uncertainty in this temperature range given climatic sensitivity; however, a level of optimism in the achievability of this target is probably required for diplomatic compromise and legally binding agreement. With current knowledge of technological development, learning curves, and investment costs, the achievability of the 1.5°C is near technically infeasible, and plays lip service to the High Ambition Coalition again for the sake of global agreement. Estimates of global abatement cost for fossil fuel and industry emissions starts at \$130/tCO_2 in 2020, and is likely to incur significant political and economic resistance once it is public knowledge what the Paris accord means economically. However, the converse, in terms of economic damages, loss of life from extreme weather events and local air pollution is as of yet unknown, and the precautionary principle dictates that globally we must act to mitigate and adapt to climate change.

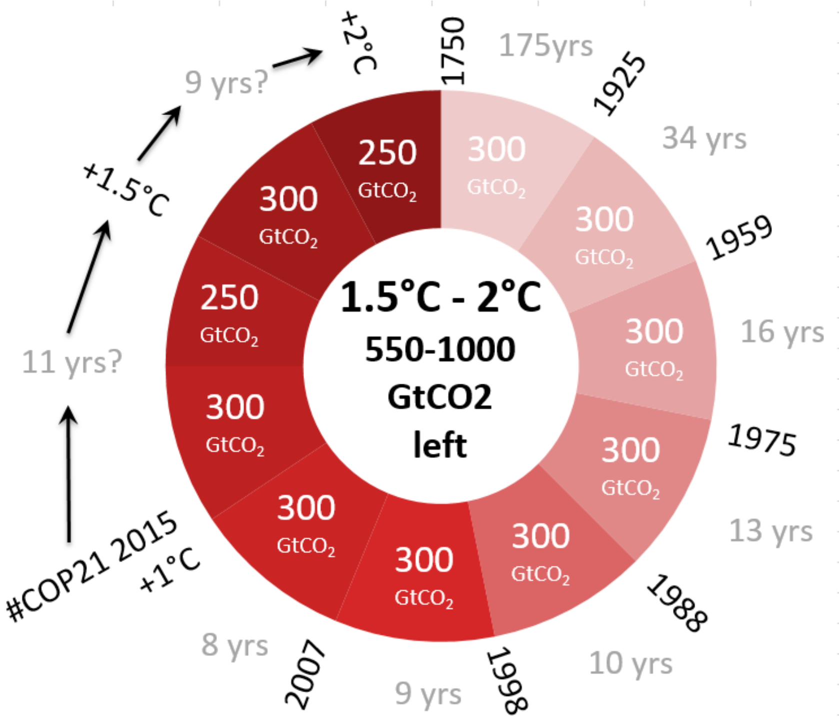

Figure 1.1 The Global Carbon Clock - Ticking down to 1.5°C & 2°C.

1.2 METHODOLOGY

This thesis uses empirical analysis and techno-economic energy system modelling to analyse in-depth aspects of Irish energy security. Hybridisation of macroeconomic feedbacks to techno-economic integrated energy systems models are used to investigate the macroeconomic consequences of Irish and global decarbonisation. Finally these methods are combined with a post optimisation algorithm to balance global macroeconomic impacts of decarbonisation to provide equity and climate justice via quantification of required inter regional green finance payments for fair effort sharing. This method combines empirical analysis accounting for regional cumulative emissions responsibility, and hybrid techno-economic modelling to assess the least cost pathway to a 2°C mitigation scenario.

1.3 AIMS

This thesis sets out with the aim to improve the evidence base underpinning energy policy decisions with a focus on energy security and equitable decarbonisation, together with the following objectives:

- Analyse historic energy security trends across all supply and demand sectors in Ireland, assessing the primary risk factors and vulnerabilities of the Irish energy system.
- Examine Irelands vulnerability to oil and gas supply and price shocks.
- Examine methods of assessing macroeconomic impacts of energy system vulnerability.
- Examine the macroeconomic impacts of decarbonising the Irish Energy System.
- Quantify the levels of green finance required based on United Nations concepts of responsibility and capacity to equitably decarbonise the global energy system accounting for historical cumulative emissions and unequal regional macroeconomic impacts.

1.4 THESIS IN BRIEF

In addition to this introductory chapter, and a final summary concluding chapter, this thesis is presented in six chapters: Chapter 2 is due to be published in a peer review report on Irish Energy Security as well as already informing the Irish Government Energy White Paper (Department of Communications, Energy, & Natural Resources, 2015; Dineen et al., 2016). Chapter 3 has been published as a peer review journal article. Chapter 4 and 5 have been published as peer reviewed book chapters. Chapters 6 and 7 are in review in Energy Policy and Nature Climate Change.

Chapter 2 reviews the qualitative energy security assessment literature, and presents an empirical energy security assessment of the Irish energy system. The chapter closes with an application of the energy security assessment method to future low ambition decreased carbon energy system pathways within the Irish TIMES energy system model.

Chapter 3 applies fossil fuel supply and price constraints on the same Irish energy system model and outlines the least cost optimum energy system under price and supply scenarios soft linked to the International Monetary Fund's DSGE monetary and fiscal policy model GIMF.

Chapter 4 outlines best practice within the IEA-ETSAP community of hybridising global and regional techno-economic technology rich integrated energy systems models moving towards and supply-demand general equilibrium.

Chapter 5 similarly outlines best practice and techniques in hybridisation of national techno-economic models giving national macroeconomic impacts of decarbonisation policies upon the energy system

Chapter 6 applies these best practices to a hybridised Irish energy system model Irish-TIMES-MACRO giving first order estimates of macroeconomic impacts of equitable decarbonisation of the energy system in Ireland.

Chapter 7 concludes with an application of hybridisation of the global technology rich Integrated Assessment Model ETSAP-TIAM. The research question and purpose in this chapter is to quantify equitable capital transfers to equalise regional macroeconomic impacts based on differing effort sharing rules.

1.5 Role in collaborations

This thesis comprises my own work and was written by me, but involved collaboration at many junctures. All chapters have been published, submitted or prepared for submission to scientific journals, scientific book series or government policy documents. Professor Brian Ó Gallachóir, my supervisor, has advised on all aspects of this thesis:

Chapter 2 is entirely my own work.

Chapter 3 is a collaborative work, whereby after meeting with the research division at the International Monetary Fund, and received training in their GIMF model, I applied scenario outputs to the Irish TIMES energy system model. I was lead author on this work, and acknowledge development contribution of the Irish TIMES energy system model with co-Authors, Alessandro Chiodi, Maurizio Gargiulo, Paul Deane, Brian Ó Gallachóir, and with preliminary review and insight from Morgan

Bazilian. Chapters 4 and 5 are highly collaborative on a global scale. I lead the organisation of 2 international workshops to gather the members of the ETSAP community engaged in macroeconomic feedback to their energy systems models. These two book chapters are the condensed proceedings of the two workshops and relevant literature review. I am the lead author of Chapter 6 leading the development and calibration of macroeconomic feedback into the Irish TIMES MACRO, Hybrid energy system model. I acknowledge the developers of the Irish TIMES energy system model as co-authors and Maurizio Gargiulo as co-author in debugging the MACRO module. For Chapter 7, the final chapter, I am the lead author, in collaboration with Socrates Kypreos providing insight in post optimisation analysis, Antti Lehtila, as co-author in implementing code changes and recommendations to the ETSAP-TIAM-MACRO source code GAMS implementation for delayed action.

Chapter 2 Energy security Assessment Methods – Applied to Past and Future Irish Energy Systems

Primary Outputs:

Glynn, J., Gargiulo, M., Chiodi, A., Ó Gallachóir, B., 2015. Energy Security Assessment Methods: Quantifying the security co-benefits of decarbonising the Irish Energy System. SI: Modelling Energy Security. Energy Strategy Reviews (In Review).

Ó Gallachóir, B., Deane, P., Chiodi, A., Glynn, J., Rogan, F., 2015. Energy Modelling to Inform the White Paper. Department of Communications, Energy and Natural Resources, Government of Ireland, Dublin, Ireland.

Confrey, E., Glynn, J. 2015. Ireland's Energy Security: challenges and opportunities. Government Department of Communications, Energy and Natural Resources. Presented at Energy Ireland Conference, 17th-18th July 2015, Dublin, Ireland.

Marie-Claire Aoun and Quentin Boulanger (IFRI); Damir Pešut, Marko Matosović and Robert Bošnjak (EIHP); Paul Deane, James Glynn and Brian Ó Gallachóir (UCC); Nathalie Desbrosses (Enerdata). Strengths and Weaknesses of the European Union gas and security of supply. INSIGHT_E; Hot Energy Topic May 2014, Issue HET no.1

Requested input:

Dineen, D., Howley, M., Holland, M., Cotter, E., Glynn, J., Byrne Ó Cléirigh Consulting, 2016. Energy Security in Ireland: A Statistical Overview. Sustainable Energy Authority of Ireland, Dublin, IRELAND.

2.1 ENERGY SECURITY INTRODUCTION

Energy security is a subjective interdisciplinary concept (Cherp and Jewell, 2011). Its qualitative definitions and resultant polysemous nature often leaves it vulnerable to exploitation as a blunt energy policy instrument (Kruyt et al., 2009; Löschel et al., 2010a). Energy security is growing in prominence in government policy lexicon (Chester, 2010; Löschel et al., 2010b), however, it remains poorly defined (Kruyt et al., 2009; Winzer, 2012) and without a strong theoretical basis (Markandya and Pemberton, 2010). The concepts of security of supply (SOS), continuity of supply, diversity of supply, supply/demand balances, reserve/production ratios, and fuel diversity, all focus on physical availability of energy resource supply under the understanding that an uninterrupted energy supply is critical for a functioning modern economy. Frameworks conceptualising energy security in terms of *availability, accessibility, affordability, and acceptability* (Cherp and Jewell, 2014, p. 4), remain general in nature without quantifiable objective energy policy goals for each concept, each receiving differing degrees of attention.

The literature on energy security quantitative metrics have put forward multiple definitions with conceptual frameworks devised from each author's discipline specific perspective (Chester, 2010; Sovacool, 2013; Sovacool and Mukherjee, 2011; Vivoda, 2010; Winzer, 2012). The extensive literature has yet to converge to formulate a unified definition of energy security. At the institutional level, the International Energy Agency (IEA) define energy security as the availability of a regular supply of energy at an affordable price (International Energy Agency and Jewell, 2011). Bohi and Toman (1993), from the political economy perspective focusing on market failure and externalities, define energy insecurity as the loss of welfare that may occur as a result of a change in the price or availability of energy (Bohi and Toman, 1993). While from a risk analysis and engineering integrated systems perspective, energy security is defined as low vulnerability and resilience of vital energy systems (Cherp and Jewell, 2011). It may be the case that energy security is too broad and complex a term to expect an agreed definition (Faas et al., 2011). Typically an energy security framework produces a singular metric devised to indicate a trend of positive or negative energy security within a given specific economy's energy system, a subsector of the energy system, or for a specific fuel or energy carrier of the energy system (Gupta, 2008; Le Coq and Paltseva, 2009; Lefèvre, 2010; Roupas et al., 2009; Scheepers et al., 2007).

Energy security varies over time from milliseconds, seconds, hours, days, years, election cycles, decades, and geological timescales given a specific area of interest (Jansen and Seebregts, 2010; Pregger et al., 2011; Seljom and Rosenberg, 2011); from electricity grid stability to primary energy supply and storage, to geopolitics and resource depletion (Cohen et al., 2011). The chosen temporal, technical, political and economic boundaries of the conceptualisation of an energy security measurement, often represented as an index (Brown et al., 2014), and its weighting method inherently bias its assessment of energy security (Cherp, 2012; Costantini et al., 2007; von Hippel et al., 2011).

It may be politically desirable to have a single metric derived from a transparent method to represent a nation's Energy security. However, in aggregating energy security indicators into an index the risks in complex dependency in the energy system supply chain can be overly simplified (Cherp and Jewell, 2011; Gracceva and Zeniewski, 2014; Pachauri and Cherp, 2011). Quantitative measures such as energy return on energy invested (EROEI) aim to be less biased (Heun and de Wit, 2012).

Areas of vulnerability are clouded as a result of apparent risk mitigation across dimensions of security, that in reality do not supply substitutable energy services (Löschel et al., 2010b). Previous studies have used expert surveys to minimise this bias and appropriately weight the relative importance of each variable for an energy security index (Cherp, 2012; de Jong et al., 2006; Scheepers et al., 2007). It still remains that this approach lacks a fundamental underpinning to bridge the interdisciplinary nature of the problem.

To date, a multitude of energy security indices have provided subjective, concept specific metrics, to start to narrow the definition of energy security and begin to enable policy makers with a quantitative picture of energy security (Bazillian et al., 2006; Cohen et al., 2011; Gupta, 2008; Jansen and Seebregts, 2010; Lefèvre, 2010; Löschel et al., 2010a; O'Leary et al., 2007; Scheepers et al., 2007).

Defining and disaggregating the interdependencies between societal welfare, environmental sustainability, economic production, economic growth, sustainable development, energy cost, price, price volatility, and energy consumption rates, provides a multidimensional perspective upon the integrated effects of energy (in)security (Ayres, 2007; Ayres and Warr, 2005; Benes et al., 2012; Bohi and Toman, 1993; Gupta, 2008; Hamilton, 2012; Heun and de Wit, 2012; IEA, 2012; Kumhof and Muir, 2012; Lindenberger and Kümmel, 2011; Solow, 1994; Waisman et al., 2012; Warr and Ayres, 2010)

This chapter focuses on an energy security index method, updating the energy security assessment for Ireland using the Energy Research Centre of the Netherlands (ECN) supply/demand index for consistent comparison to previous international studies (Dennehy et al., 2011; Scheepers et al., 2007). The results look both into the past, and forward, using historical data and future scenario techno-economic least cost optimised energy systems for differing decarbonisation and carbon tax scenarios from the Irish-TIMES energy system model (Ó Gallachóir et al., 2015). The following chapter applies energy security criteria to a national energy system model to explore differing systemic interdependences of resource constraints also upon the Irish energy system security. The ECN Supply/Demand index maintains a balance between supply and demand side risk as well as balance between comprehensiveness and transparency. As indicated from the above review; there is no perfect measure of energy security, but this is one of the better approaches. The change in perceived security is assessed here with methodological updates by editing the Supply/Demand index to account for origins of primary energy supplies rather than the current risk associated with the import partners. The positive weighting of EU re-sellers as opposed to non-EU producers of primary energy commodities and resultant bias is outlined in the discussion.

The rationale being that primary energy suppliers to Ireland, both directly and indirectly via the UK, are changing from historical market trends. The shift in energy supply origins is driven primarily by the decline of oil and gas production in the North Sea, and the surge in unconventional oil and gas production in North America (Miller, 2011; Sorrell et al., 2010b). Commodity arbitrage is creating new balance of trading partners and with it new perceptions of risk and security of supply.

2.2 Methods Applied

The Supply/Demand index (S/D) is a measurement of medium to long term energy security of the whole energy system. The Supply/Demand index was developed as an energy security indicator by the Energy Research Centre of the Netherlands (ECN) and Clingendael International Energy Programme (CIEP) and proposed as a European standard for energy security assessment (de Jong et al., 2006; Scheepers et al., 2007). Multiple other energy security metrics are suitable for sector specific analysis at higher temporal resolution assessing sectoral vulnerability to specific risk factors (Bazillian et al., 2006; Leahy and Tol, 2011). For example, the power transmission system operator publish an annual generation adequacy report where they compute the hours of loss of load expectation of the power system. The gas system operator similarly computes the gas capacity adequacy statement planning for a one in fifty year peak demand event, akin to the winter of 2010. The S/D Index on the other hand takes a systematic view, including both supply and demand side elements, covering final energy demand, energy conversion and transmission (C&T), and primary energy supply (PES). The energy system is represented below for 2014 in the sankey diagram Figure 2.1. Energy flows from the country of origin of primary energy supply on the left, through conversion and transmission stages, to sectoral demand for final energy consumption on the right. The magnitude of those energy flows are represented by the thickness of the connecting paths coloured by energy type, visualising import dependency, primary energy shares, supplier diversity, fuel diversity, electricity fuel mix, efficiency, and total final consumption shares per sector.

This approach expands the Index into a time series within the constraints of historical data availability, updating the index to 2014, and further aims to account for the changing nature of the UK primary energy supply as indicated as important in the previous energy security report in the SEAI energy security in Ireland series (Dennehy et al., 2011; O'Leary et al., 2007). The EU-27 score in 2005 was 65%, and

62% in 2020 (Scheepers et al., 2007). The summary scores are outlined in Table 2.1. The first row outlines the S/D index score for the case where Irish imports of refined petroleum products and natural gas imports via the UK are weighted to take account the percentage of UK Oil and Gas imports that originate outside the EU or Norway. The second row, shows the S/D score without this adjustment for UK primary energy supply.

S/D Index Score	2000	'05	'08	'09	'10	'11	'12	'13	'14
UK Adjusted	68	66	62	59	57	57	53	59	57
UK Not Adjusted	77	77	75	78	77	78	68	75	72

Table 2.1 Energy security supply/demand index scores. Scores with and without accounting for the increasing import of Non-EU Oil and Gas into the UK Primary Energy Supply (Score from a total of 100)

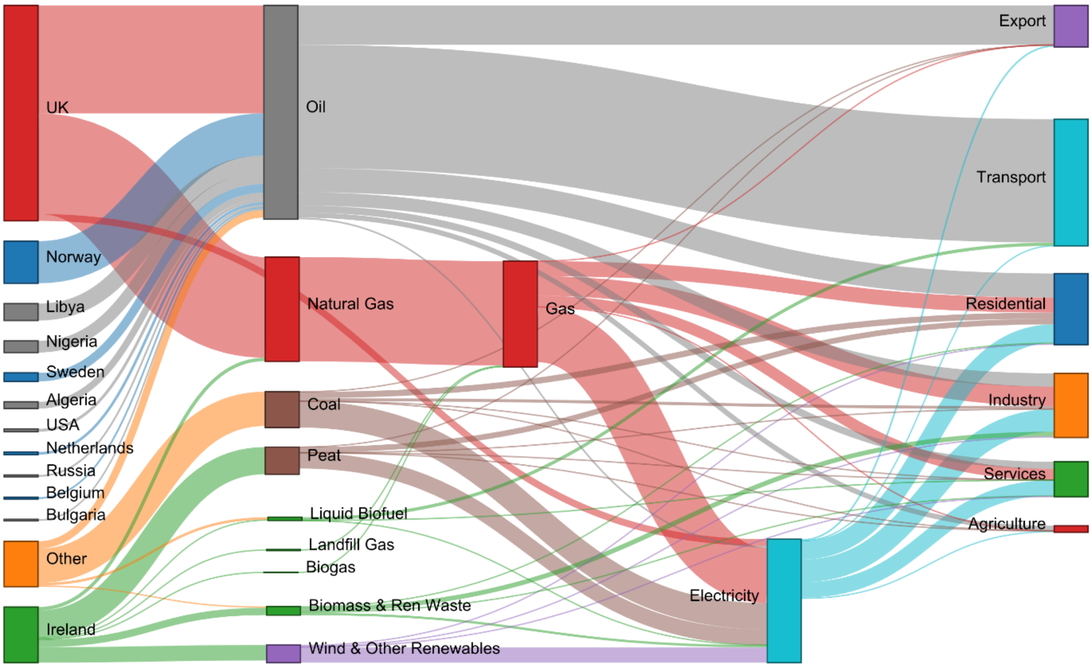

Figure 2.1 Ireland Energy System Sankey Diagram – 2014 (Data: IEA/SEAI)

2.3 Description of the Supply/Demand Index Method

The S/D index compiles quantitative and qualitative data in assessing the energy system security. Quantitative data is used in weighting the sectoral demands proportionately to sectoral final energy consumption, as is primary energy supply weighted by the commodity shares of total primary energy requirement. Each element in the structure of the index shown below in Figure 2.2 is comprised of a weight and a score. Scores are calculated by quantitative data measuring relevant technical characteristics of the energy system, scored within a qualitative range of 0-

100 and weighted according to the relative importance to overall energy security of the system. The qualitative weights of each element, which reflect the perceived vulnerabilities of each element of the index, were decided upon by expert survey and review in the original construction of the index, and as such are subjective and open to scrutiny on a country by country basis (Scheepers et al., 2007). The sum of the product of the weight and score of each level of the index structure gives an overall energy security score out of 100. The scoring rules, qualitative weights, and demand benchmarks largely remain the same as in previous versions to allow international comparison. However, updated datasets are used and give rise to some changes in the S/D score for previous assessments. As already mentioned there is one significant change to the quantification and scoring of imported Oil and Gas via the UK. Irish imports of Oil and Gas from the UK are weighted as from EU + Norway (NO) or Non-EU in proportion to the percentage of UK imports originating from outside the EU. This is implemented in an effort to account for the chain of supply of UK primary energy imports, given the heavy dependence Ireland has on the UK for primary energy supply of both refined petroleum products and natural gas. This has a strong influence on the overall index score given the dominant weighting primary energy supply receives, and the dominant scores oil and gas receive as a result of their proportions of primary energy requirement. The data input, structure, and results of the S/D index are detailed in the following sections.

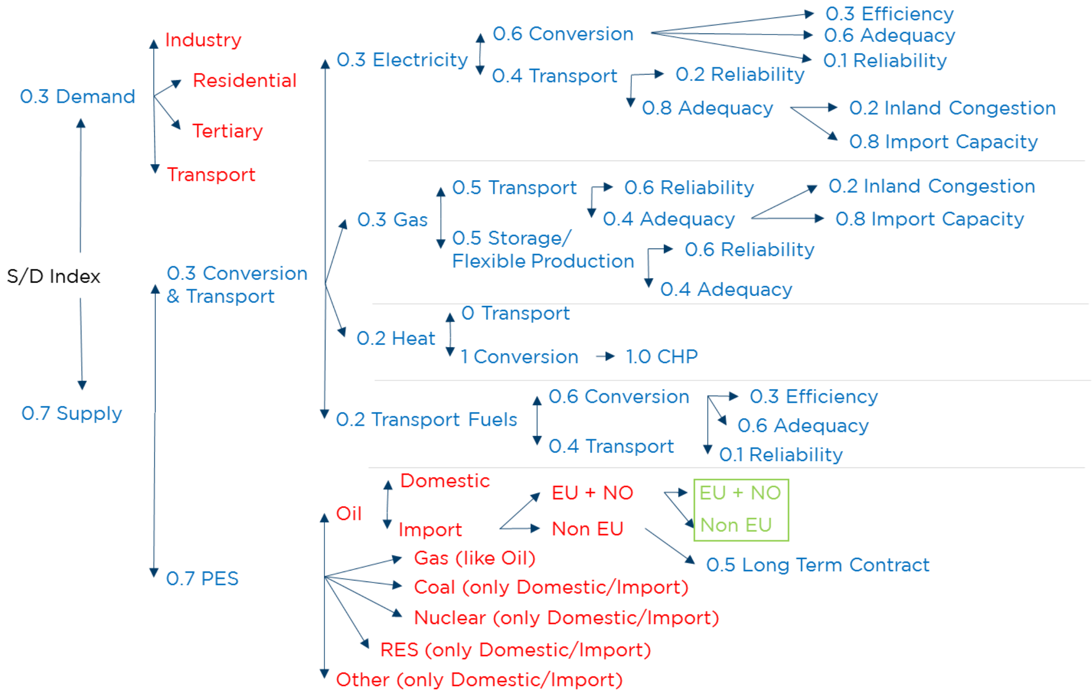

Figure 2.2 Supply/Demand index weighting and scoring structure (Adapted from (Scheepers et al., 2007)). Red elements are weighted quantitatively in proportion to Total final consumption and total primary energy supply, whereas blue elements are weighted by expert review survey for each element's appropriate importance.

2.4 Data Sources

This section outlines the primary data inputs, trends and the data sources.

2.4.1 *Demand*

Energy demand intensity is benchmarked against the average of top 5 EU member country scores to give a relative score for demand security for each sector. The average of the best demand intensities of the top 5 EU-15 countries is used to create the benchmark for all sectors other than the residential sector, where the average of the top 5 EU-25[1] member states creates the benchmark score for residential energy demand intensity. The same EU benchmarks which are based on 2003 data are used for consistency. The sectoral charts in Figure 2.3 show Irish energy demand intensities relative to a time series of EU benchmarks for each year.

[1]EU 25 is the EU-27 group less Bulgaria and Romania and was the European Union enlargement acronym existing between 1st May 2004 to 31st December 2006.

Irish Industry in 2014 is seen as having low energy intensity per value added of 72.3 toe/M€$_{2005}$GVA, and is lower than the EU benchmark therefore receiving a high score of 100%, highlighting energy efficiency and the high value added nature of Irish Industry. The tertiary sector is seen to be in transition from higher energy intensity before the great recession, to below the EU benchmark more recently. The tertiary sector energy intensity in 2014 is 14.4 toe/M€$_{2005}$GVA and is now below the benchmark, and so it receives a 100% score in 2014. All other sectors exhibit higher energy demand intensities relative to the EU benchmarks and are scored accordingly. The residential sector is reducing its energy intensity on a per capita basis, most notably post 2008. A decomposition analysis is required to parse out what is the effects of economic recession, energy poverty and housing energy efficiency. In 2014 the residential energy demand intensity had dropped to 0.55 toe/capita, still above the EU benchmark of 0.29 toe/capita. Passenger transport has approximately double the demand intensity of the EU benchmark on energy per passenger kilometre basis, at 65 toe/Mpkm and 31.6 toe/Mpkm respectively. Post 2008, freight transport demand intensity rose slightly to 63.5 toe/Mtkm compared to the EU benchmark of 35.7 toe/Mtkm in 2014. Notably the overall energy consumption of the transport sector decreases post 2008 as a result of the energy service demand collapse for transporting heavy aggregates primarily for the building sector.

Each of the sectoral demand intensities are weighted by their proportion of total final energy consumption (TFC) in any given year. Transport dominates the assessment to demand security given is growth from 38% TFC in 2000, to 43% TFC in 2007, to 42% in 2014.

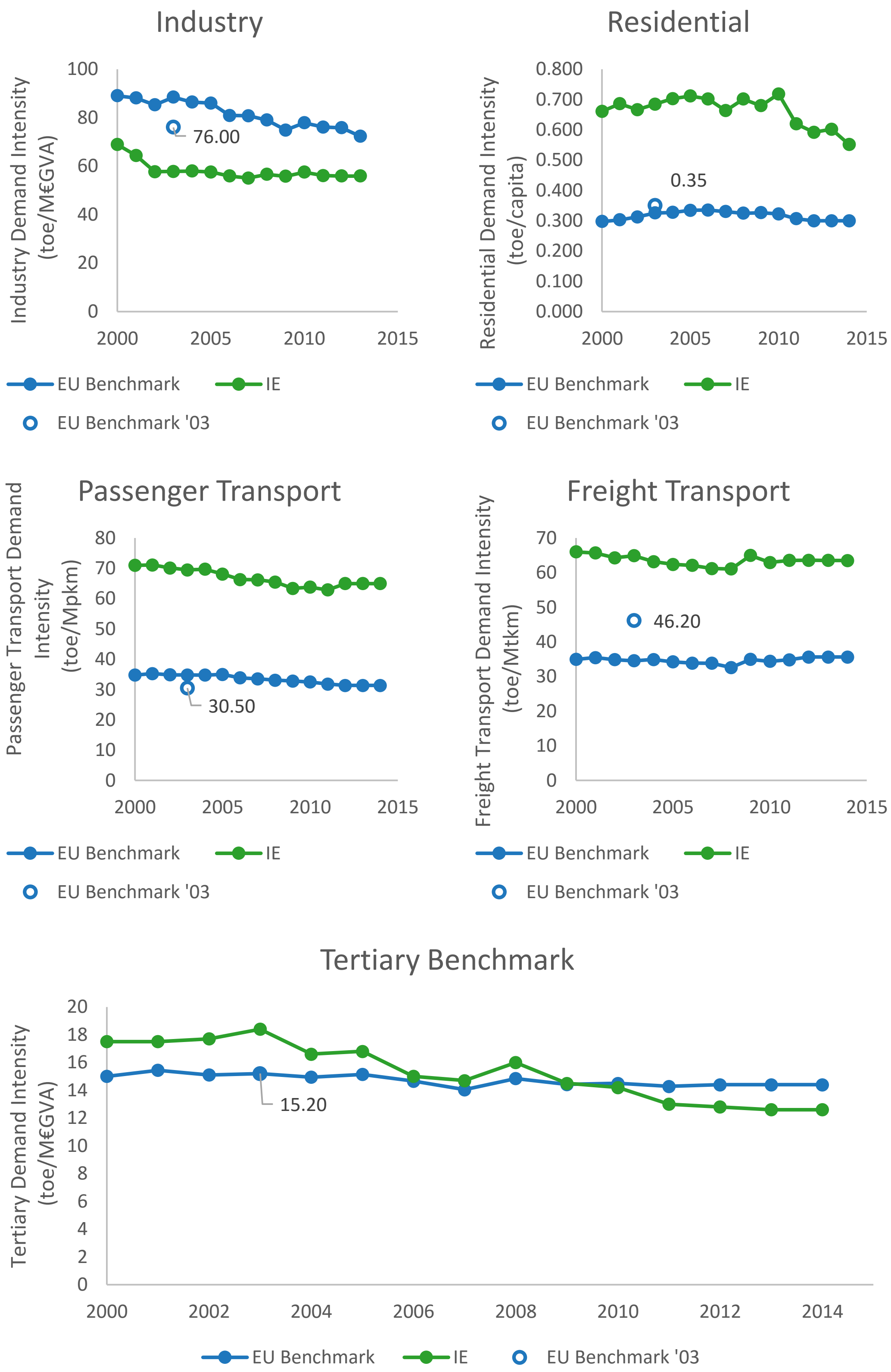

Figure 2.3 Energy demand intensity and European benchmark for each sector of the Index (a) Industry, (b) Residential (c) Passenger transport, (d) Freight transport, (e) Tertiary (Data: ODYSEE/SEAI – preliminary 2014 data) EU Benchmark '03 is calculated using the same data from 2003 and method from the original methodology report to calculate a single benchmark, while new data is available and changes the benchmark time series relatively to the original.

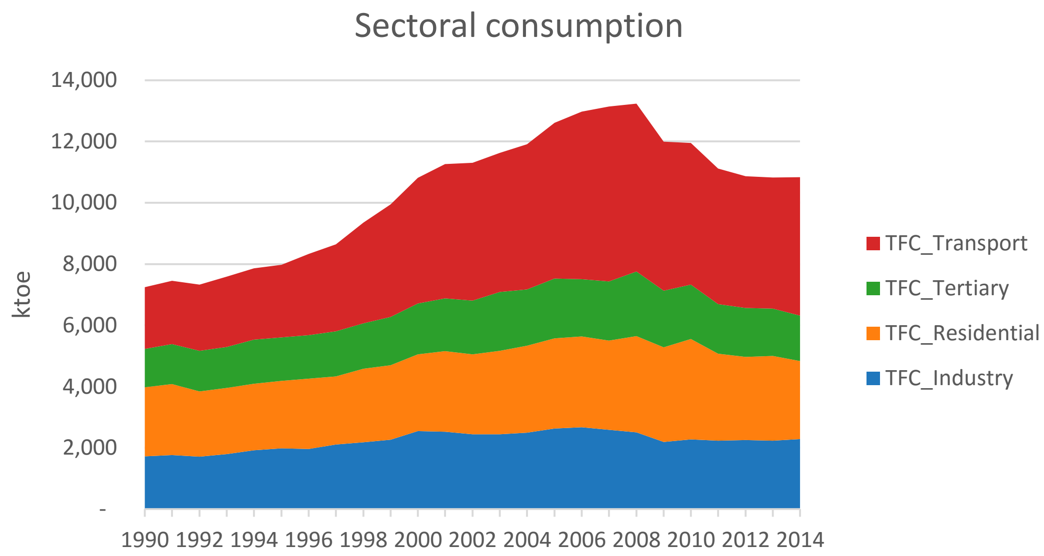

Figure 2.4 Sectoral final energy consumption (Data: SEAI)

2.4.2 Supply - Conversion and Transmission

The conversion and transmission (C&T) element of supply gives dominant weighting to electricity and gas. These sectors and their input data is outlined below. The remaining sections of the conversion and transmission branch of the S/D index is made up of Heat and Transport fuels.

Given the lack of heat conversion and transmission in Ireland, heat security is simply scored as the level of electricity generated from combined heat and power (CHP) plants as a percentage of all electricity generation available for final consumption. In 2014 CHP generated electricity made up 3.8% of electricity available for final consumption.

Transport fuel security is based on the efficiency and reserve of refining capacity in any given year. Whitegate refinery is the only refinery in Ireland, and their production slate is dependent on many variables but largely profitability is dictated by the volatility at the margin of crude oil prices. Strategically Whitegate refinery provides security in maintaining up to a 20% reserve capacity for domestic production of transport fuels. Transport fuel security is scored accordingly as a function of the ratio of the refinery annual output and maximum capacity in the range of 80% - 95% maintaining a reserve margin for strategic security.

2.4.2.1 *Electricity*

The security of the electricity branch of conversion and transmission is scored with multiple data inputs quantifying efficiency, adequacy and reliability. The generation efficiency of thermal plant excluding non-dispatchable renewables is seen to have stabilised at 47.2% in 2014. This excludes the effects of supply efficiency from own uses, transmissions losses, imports, exports or the input from wind energy. Import capacity factor is calculated as the ratio of import capacity to installed dispatchable capacity. Given the outages in the Moyle interconnector to Scotland and the newly commissioned east west interconnector (EWIC) to the UK, the import capacity factor has risen accordingly to over 10% recently, but has dropped below 10% in 2014 due to new installed capacity, and reduced interconnection capacity due to interconnector line faults. Generation adequacy is scored relative to the generation reserve factor, which is the ratio of installed dispatchable capacity and peak demand in any given year. A score of 1.2 or above is seen as sufficiently secure.

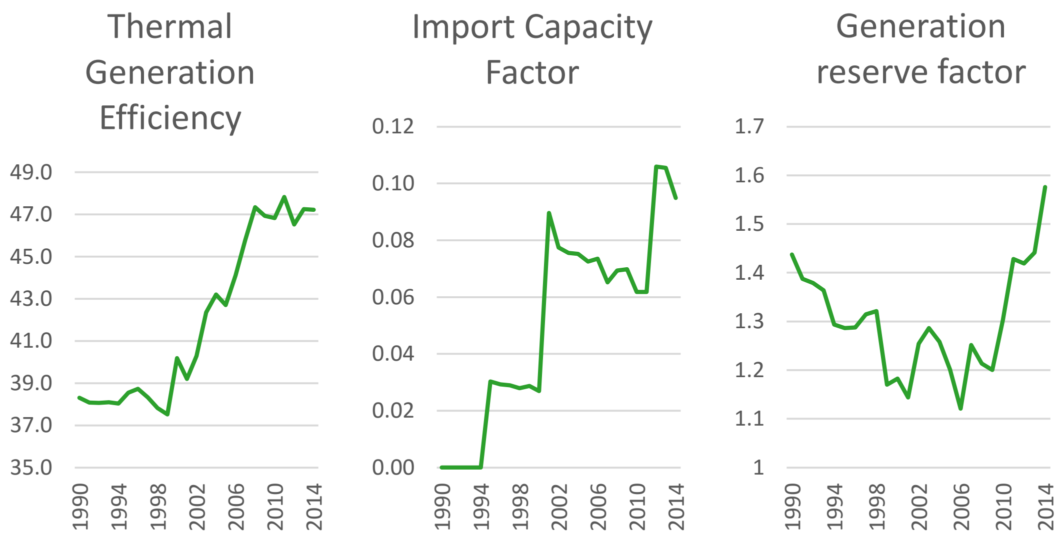

Figure 2.5 Electricity conversion and transmission system security characteristics (Data: SEAI/EIRGRID/EUROSTAT)

2.4.2.2 *Gas*

The gas conversion and transmission security score is dependent upon the network adequacy and reliability of transmission, storage, and flexible production. The input data is presented in Figure 2.6. These measures characterise annual and peak demand trends. The import reserve factor is the ratio of the import capacity of the Moffat interconnector less the reserved capacity for Northern Ireland to the annual gas imports of the Republic of Ireland. In 2014 there is over 50% reserve capacity on the gas import infrastructure on average over the year. The demand swing factor is the ratio of monthly peak demand verses the average monthly gas demand in any given year, to measure the volatility between summer trough and winter peak demand. The unusually cold weather events that occurred in the winters of 2009/10 and 2010/11[2], both caused large demand swing in range of 30% between the average and peak gas demands. This is seen more clearly in Figure 2.7 showing monthly domestic gas demand for the years 2008 to 2014. Shorter term gas storage and flexible production is measured as the ratio of monthly peak gas production and peak (underground) gas storage output per month to peak monthly gas consumption in any given year. Domestic gas production from the Kinsale gas field is plotted in Figure 2.8, and as is seen is currently in decline, providing reduced seasonal storage services. Flexible production and or storage in the form of Corrib gas and or Shannon LNG will improve this metric.

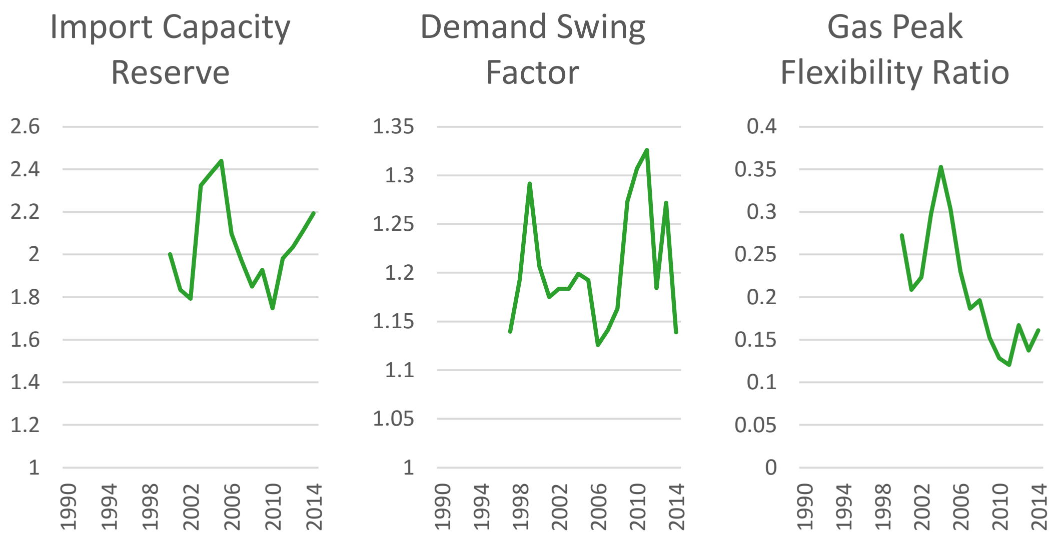

Figure 2.6 Gas conversion and transmission system security characteristics (Data: GNI/CER/EUROSTAT)

[2] MET Eireann Monthly Reports Archive - http://www.met.ie/climate/monthly-weather-reports.asp

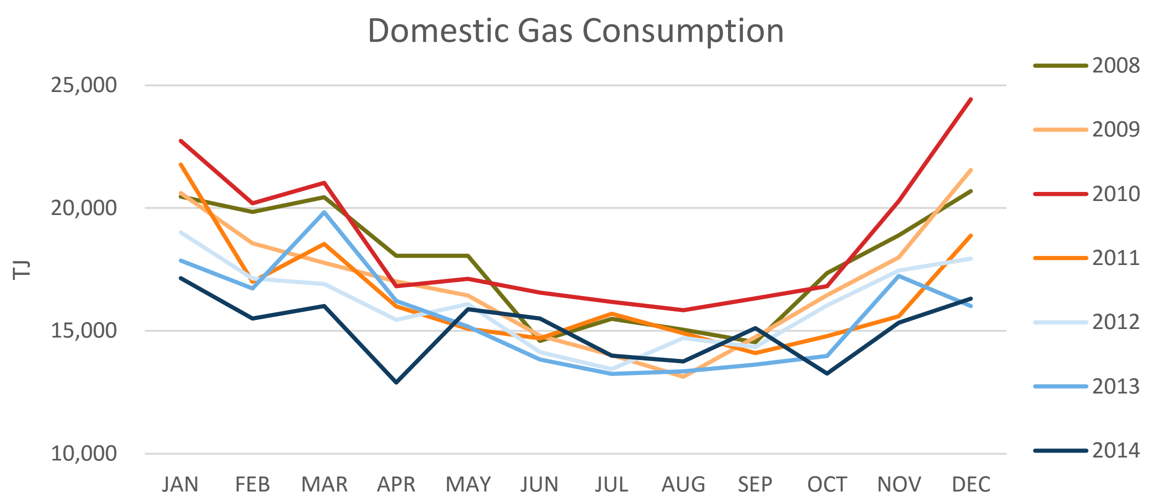

Figure 2.7 Monthly domestic gas consumption (Data: EUROSTAT)

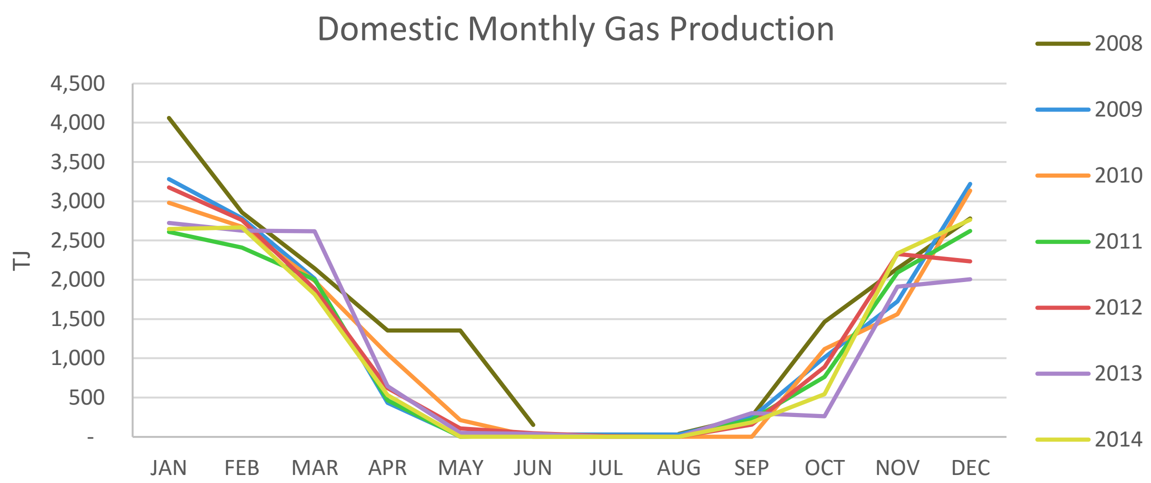

Figure 2.8 Monthly domestic gas production. (Data: EUROSTAT)

2.4.3 Primary Energy Supply

Primary energy supply underpins the transmission, conversion and provision of energy service demand, and as such is heavily weighted in the S/D index. The weight of each fuel type in primary energy supply is calculated as the ratio of the fuel primary energy requirement to total primary energy requirement. In 2014 oil was 47% of primary energy requirement, gas was 28%, solid fuels in the form of coal and peat were 18%, renewable energy sources provided 8%, while other non-renewable wastes and electricity imports provided 2%. The dominance of imported oil and the long term trends in increased gas supply are seen in Figure 2.9. 2014 saw the first appreciable rise in primary energy supply of oil up to 6,249 ktoe, from the declining trend since the 2008 level of 8,961 ktoe. Primary requirement for gas continues to decline in 2014 to 3,721 ktoe from 4,692 ktoe in 2008. Gas input into electricity generation continues to decline to 1,973 ktoe in 2014 from 3,025 ktoe in 2008, with reduced electricity demand and the continued rise of wind generation contribution to the electricity mix up to 422 ktoe in 2014.

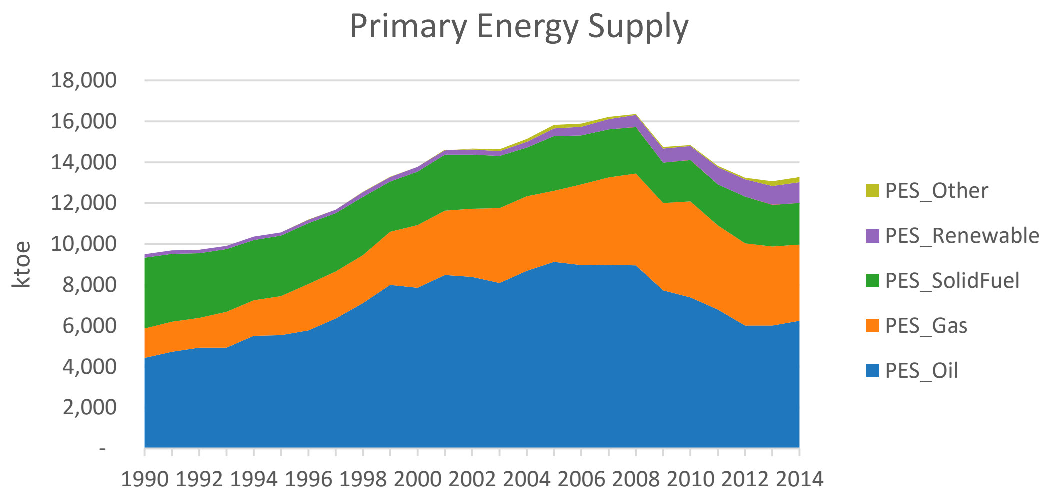

Figure 2.9 Primary energy supply by fuel type (Data: SEAI)

The ratio of imported primary energy requirement to total primary energy requirement gives the measure of import dependency. Irish import dependency declined marginally in 2014 to 86.3% from 89% the previous year. The EU has had a slowly upward long term trend in import dependency with a recent stabilisation. EU import dependency in 2013 was 53.2%. As illustrated in Figure 2.1, Ireland imported 7,688 ktoe of oil, gas and electricity from the UK in 2014. Ireland also exported 1,406 ktoe of crude oil and refined products in 2014. The UK rate of increase of import dependency, coincident with the decline rates of production of North Sea oil and gas, is a considerable indication of Irish energy security. The UK became net energy importers in 2004, at an import dependency that year of 4.5% rapidly rising in 2014 to 46.2%. It is for this more recent energy importer status of the UK, that this update to the S/D index reweights Irish imports of oil and gas from the UK, by the proportion of imports into the UK from the EU and Norway, and Non-EU countries.

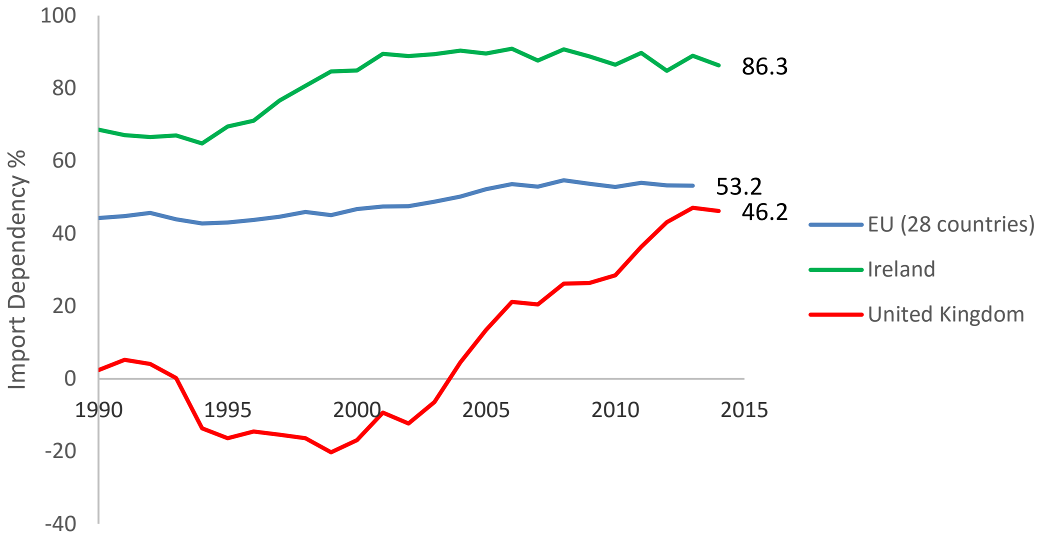

Figure 2.10 Irish, EU-28 and UK Import Dependency (Data: Eurostat)

Total supply of oil to Ireland follows the decline from the peak of consumption of oil products in 2007, as well as more recent reductions in output from the Whitegate refinery to 2,871 ktoe in 2014. As mentioned previously, 2014 has seen an increase in primary energy requirement for oil, which is net of oil exports. From 2008 onwards, there has been a considerable increase in the supply of crude oil from non EU countries, and by proxy non-EU supply as a proportion of the import mix from the UKs own imports. 49% of UK oil imports originated outside the EU in 2014, while 51.4% of crude oil imports to Ireland originated outside the EU. Reweighting UK oil product imports to Ireland by their EU vs Non EU distribution of suppliers, as well as direct product imports from non-EU countries shows non-EU oil product imported to Ireland at 47.3%. Accounting for UK oil supplier diversity, overall Irish oil imports from the EU and Norway account for 51.3% of supply in 2014.

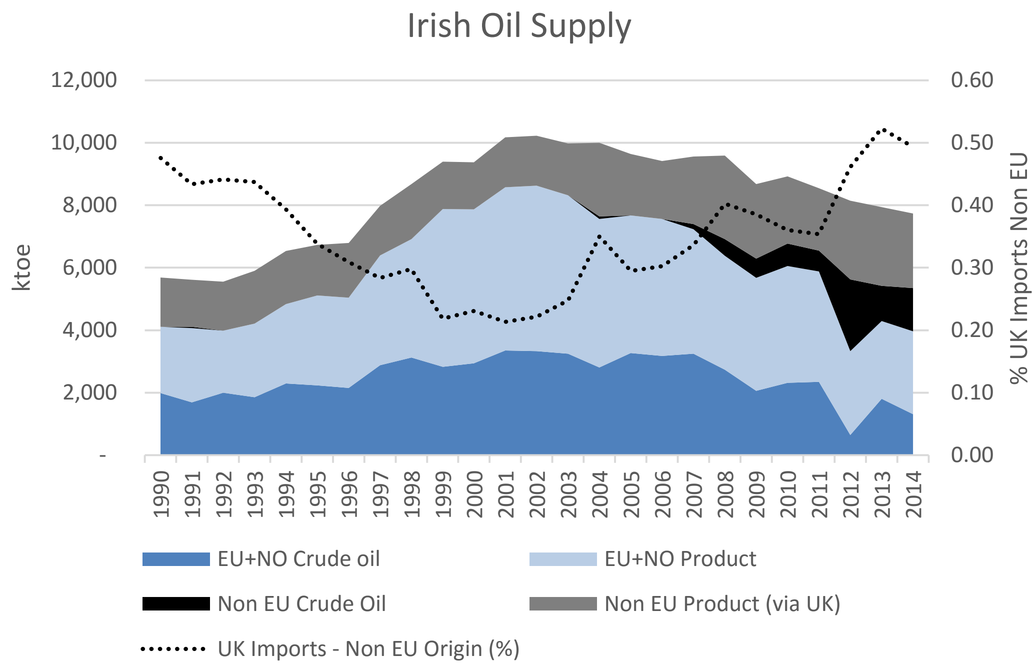

Figure 2.11 Irish oil supply history by EU and Non-EU supply origin (Data: EUROSTAT)

Indigenous gas production of 123 ktoe accounted for 3.3% of gas primary energy supply in 2014. The remainder is imported via interconnectors to Scotland and the UK gas transmission system. Gas imports from the UK are also reweighted to account for the proportion of UK supply to Ireland that originated outside the EU.

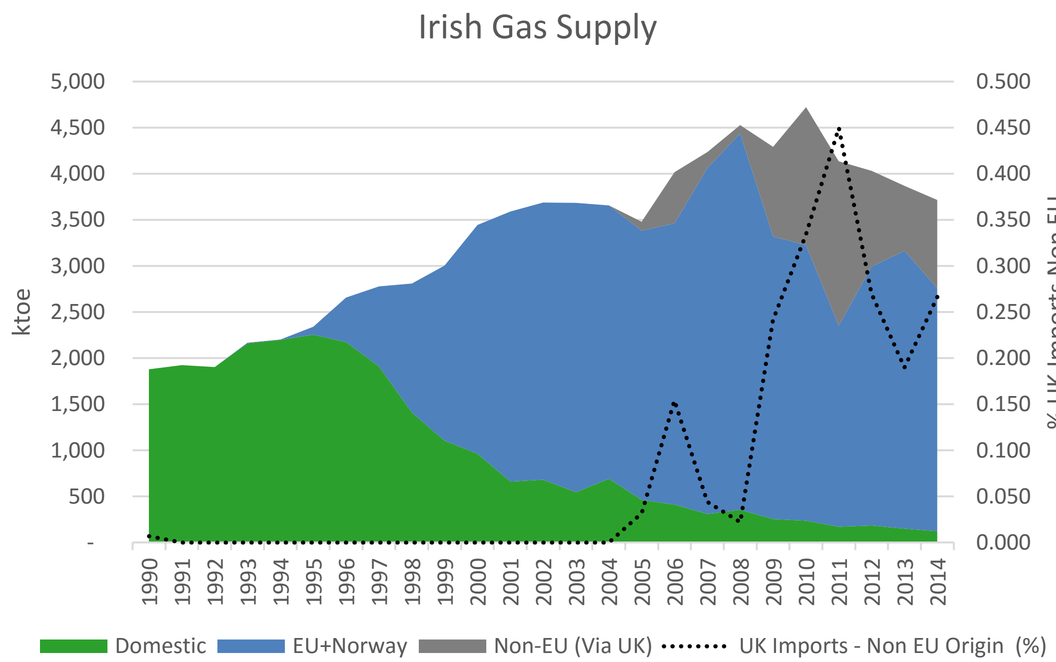

Figure 2.12 Irish gas supply by EU and Non-EU supply origin (Data: EUROSTAT)

2.4.3.1 UK Primary Energy Supply Balance

The UK department of energy and climate change (DECC) digest of UK energy statistics (DUKES) chapter 3[3], points to declining UK crude oil production, declining UK refining capacity, declining UK petroleum product output, and a mismatch between the slate of products produced in the UK, and UK product demand. All these factors contribute to the increasing level of non-EU imports of both crude oil and petroleum products to balance UK oil demand. The UK has a legacy overcapacity of refineries, whose demand is not met by domestic oil production. While the UK continues to export large levels of refined oil products, the UK has been a net oil importer since 2004, requiring increased imports from the EU, and increasingly from further afield (See Figure 2.13). In 2014 UK oil production was 39,698 ktoe, down from the 1999 peak of 137,421 ktoe, with consumption at 69,341 ktoe.

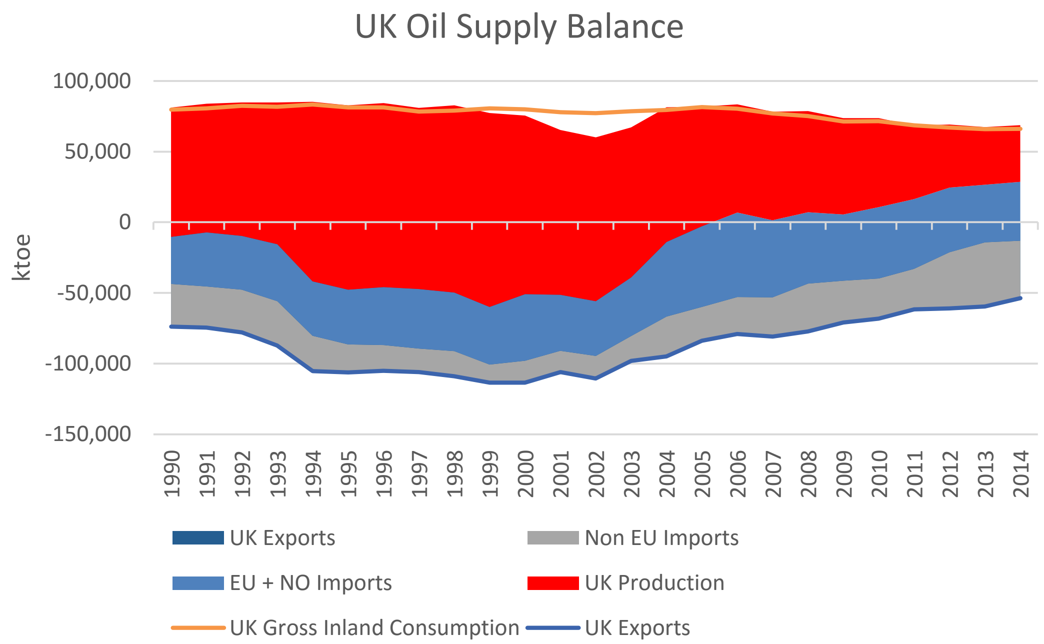

Figure 2.13 UK oil supply balance (Data: EUROSTAT/DECC/BP)

UK gas production peaked at 97,537 ktoe in 2000, there after gas production declined at 9.2% year on year over at a 10 year average from 2000 to 2010, while

[3] https://www.gov.uk/government/statistics/petroleum-chapter-3-digest-of-united-kingdom-energy-statistics-dukes

imports rose at 36.7% year on year. UK gas consumption was 87,647 ktoe in 2004 and has declined to 60,007 ktoe in 2014, -3.7% year on year over 10 years. In 2014 LNG imports from non EU countries made up 27% of UK gas imports, while the EU-28 as a whole imported 65.3% of gas in 2013[4].

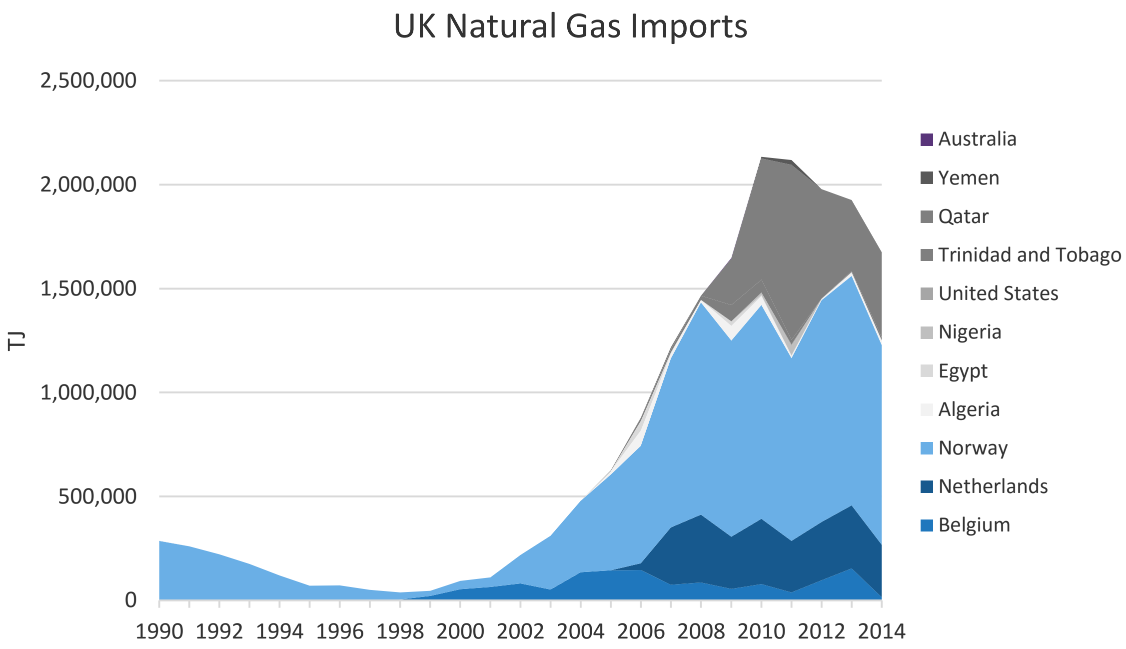

Figure 2.14 UK gas imports by origin (Data: EUROSTAT/DECC)

2.5 Results - Energy Security in the Past

The results of the S/D index based on the available datasets are presented in the following this section.

2.5.1 Demand

The maximum score of the demand element of the S/D index in any given year is 30. In 2014 demand security scored 21.2 (70.8%). The long term demand intensity trend is stable with reductions in residential demand intensity more recently (See Figure 2.15). The tertiary sector increases its demand security score when comparing these updated data sets to the previous 2008 S/D index update. Industry accounts for 21% of TFC in 2014, and with an energy demand intensity lower than the top 5 EU countries, receives a maximum score of 6.3 (100%). The residential

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4 EUROSTAT - http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdcc310

sector accounts for 23% TFC, with a score of 4.5 (63.5%). The tertiary sector receives a maximum score of 4.1 (100%). Demand security in transport is increasing primarily as a result of lower energy demand intensity per passenger kilometre. Transport consumes 42% of TFC, and receives a score of 6.3 (50.5%).

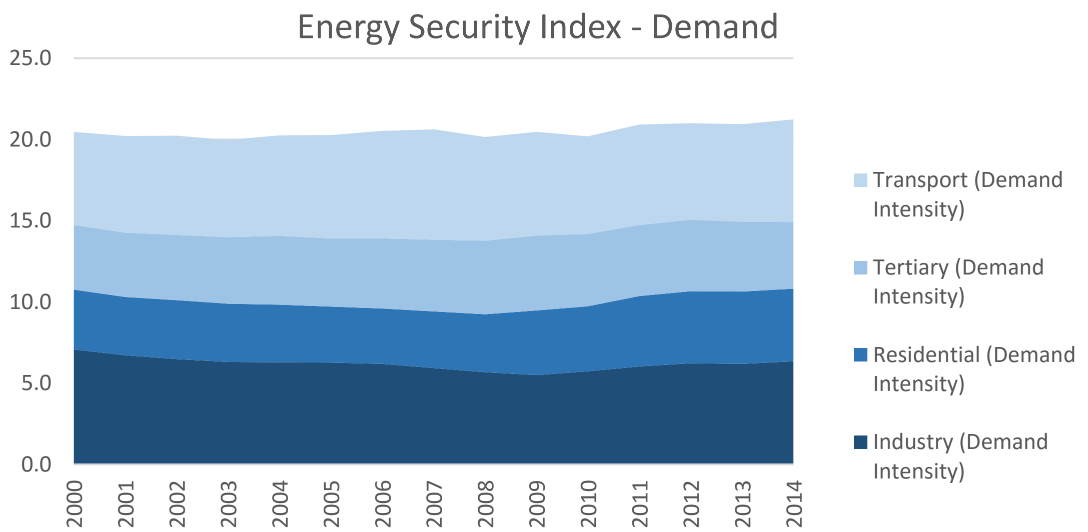

Figure 2.15 Demand Energy Security Scores

2.5.2 Supply

2.5.2.1 Conversion and Transmission

The maximum score for the conversion and transmissions (C&T) branch of the S/D index is 21. Compared to previous updates for 2008, this dataset shows the electricity sector scoring higher than previous assessments while, the conversion of transport fuels is assessed to be slightly worse. Gas and heat assessments show largely similar results. Given increased interconnector capacity above the recommended EU threshold, increased thermal efficiency, and reserve capacity above peak demand, the electricity sector receives a near maximum score of 6.1 (96.5%). The assessment of gas conversion and transmissions security is reduced as a result of the low levels of flexible production or flexible storage. Gas C&T branch scores 4.1 (65.4%). Heat is a small proportion of the S/D index, governed by the proportion of CHP in the electricity generation mix. Heat C&T scores 1.4 (33.5%). Oil refining for transport fuels sees a growing security score as a result of spare refining capacity providing strategic reserve. Transport fuels in refining and distribution scores 3.8 (90.5%) in 2014, however historically there is seen to be volatility in this score dependent upon the utilisation factor of refining capacity in the Whitegate refinery (See Figure 2.16).

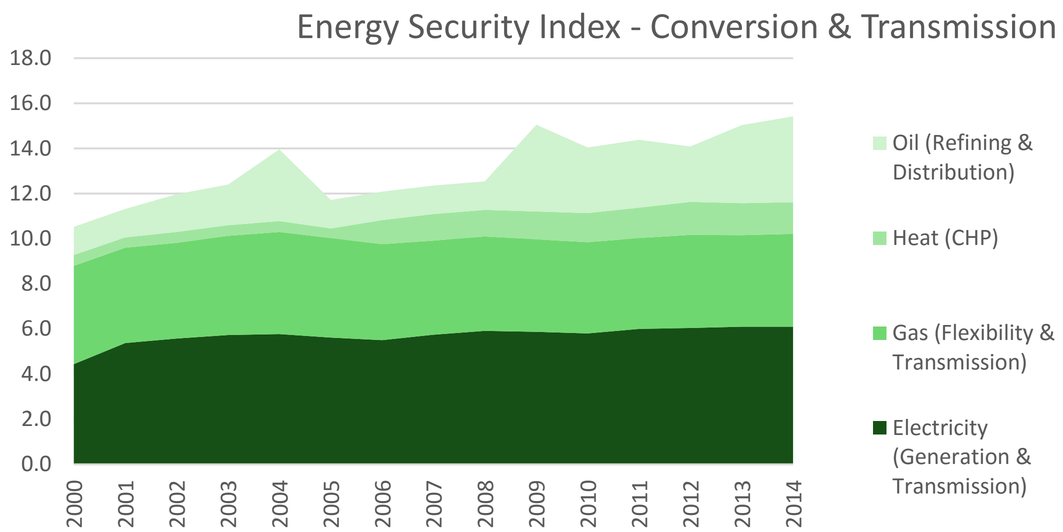

Figure 2.16 Conversion and Transmission supply security

2.5.2.2 *Primary Energy Supply*

The maximum score the primary energy supply branch of the index is 49. As already outlined, given the change in method of weighting UK imports by their proportion of origins from within the EU and Norway, or from further afield, there are considerable differences in the primary energy security score comparing to previous studies. Primary energy supply of crude oil and refined products is seen to have reduced most considerably to 3.6 (15.6%) in 2014. It is worth noting that short term oil security on island as a result of increased strategic storage of oil products has improved greatly in recent years to 90 days strategic oil reserves[5]. However the S/D index aims to take medium to long term trends into consideration, prioritising the perceived risk of country of origin of PES. Primary supply of natural gas following the same reweighting method for UK imports from outside the EU shows a declining trend, scoring 6.4 (46.7%) in 2014. The security of coal supply is stable scoring 6.3

[5] National Oil Reserve Agency - http://www.nora.ie/oil-stocks.138.html.
Emergency Response of IEA Countries - http://www.iea.org/publications/freepublications/publication/energy-supply-security-the-emergency-response-of-iea-countries-2014.html

(83.9%) in 2014. Notably the increasing trend in renewable penetration of both wind and bioenergy are increasing the security of primary energy supply as a result of largely domestic production. Renewable primary energy supply scores 3.6 (96.1%).

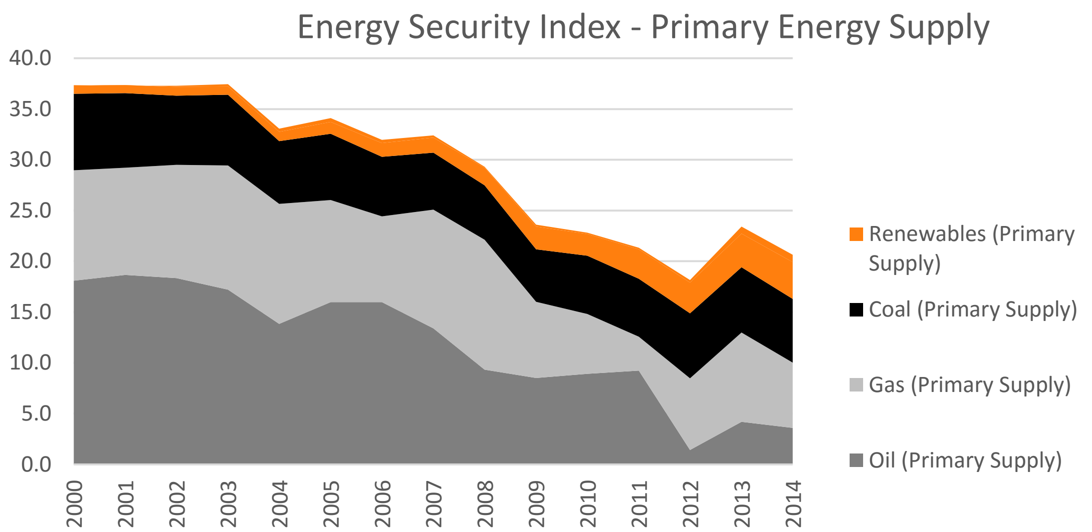

Figure 2.17 Primary energy supply security scores

2.5.3 Conclusion

The overall comparison and relative weighted scores of each branch of S/D index is seen in Figure 2.18. The case where no adjustment to the primary energy supply for the UK import mix is also presented for contrast, and comparison to previous S/D updates for Ireland. Overall the elements under domestic control on the demand side and the supply element of conversion and transmission are improving. The increasing penetration of domestic renewable energy sources is aiding in slowing the overall decline in security of primary energy supply. However, given the weighting for perceived risk that non-EU suppliers of oil and gas receive in this method, the security of Irish primary energy supply is the dominant factor in determining a declining overall security of supply. Energy security has declined in recent years with or without considering the proportion of UK imports that originate from outside the EU.

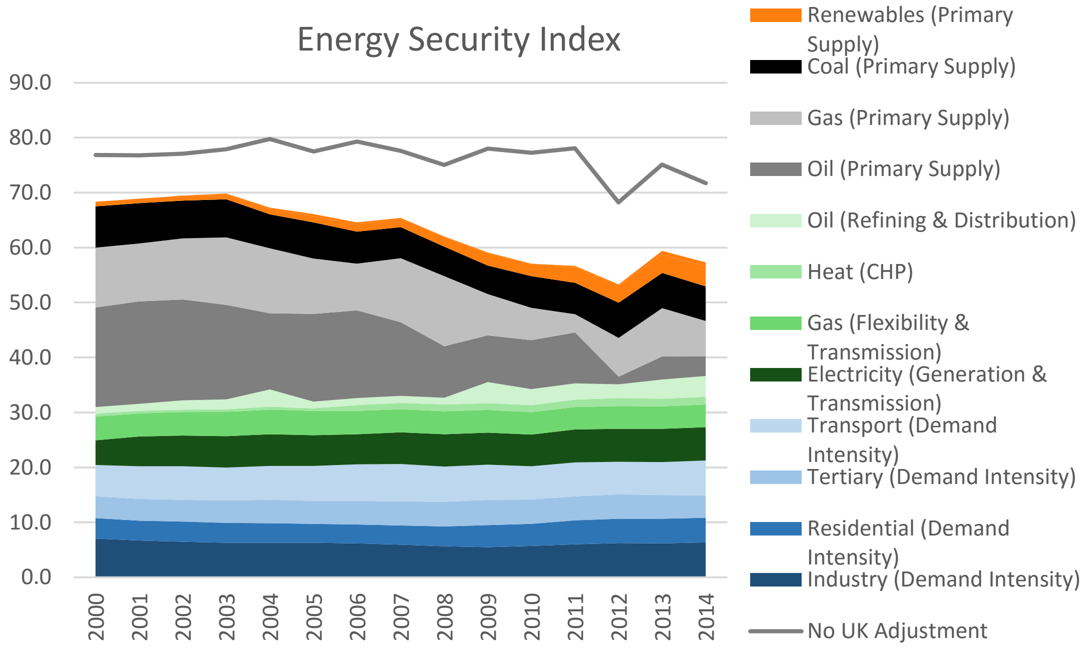

Figure 2.18 Energy security supply/demand index

	2008			2010			2012			2014		
	Weight	Score	Result	Weight	Score	Result	Weight	Score	Result	Weight	Score	Result
S/D Index			**62**			**57**			**53**			**57**
S/D Index - No UK Adjustment			**75**			**77**			**68**			**72**
Demand Intensity	**0.3**	**67.2**	**20**	**0.3**	**67.3**	**20**	**0.3**	**70.0**	**21**	**0.3**	**70.8**	**21**
Industry	*0.19*	100	**5.7**	*0.19*	100	**5.7**	*0.21*	100	**6.2**	*0.21*	100	**6.3**
Residential	*0.24*	50	**3.6**	*0.27*	49	**4.0**	*0.25*	59	**4.4**	*0.23*	63	**4.5**
Tertiary	*0.16*	95	**4.5**	*0.15*	100	**4.5**	*0.15*	100	**4.4**	*0.14*	100	**4.1**
Transport	*0.41*	51	**6.4**	*0.39*	52	**6.0**	*0.40*	50	**5.9**	*0.42*	50	**6.3**
Supply	**0.7**	**60**	**41.8**	**0.7**	**53**	**36.9**	**0.7**	**46**	**32.3**	**0.7**	**52**	**36.1**
Conversion & Transmission	**0.3**	**59.7**	**12.5**	**0.3**	**66.9**	**14.0**	**0.3**	**67.1**	**14.1**	**0.3**	**73.4**	**15.4**
Electricity	*0.30*	94	**5.9**	*0.30*	92	**5.8**	*0.30*	96	**6.0**	*0.30*	97	**6.1**
Gas	*0.30*	67	**4.2**	*0.30*	64	**4.0**	*0.30*	66	**4.1**	*0.30*	65	**4.1**
Heat	*0.20*	28	**1.2**	*0.20*	31	**1.3**	*0.20*	35	**1.5**	*0.20*	34	**1.4**
Oil	*0.20*	30	**1.3**	*0.20*	69	**2.9**	*0.20*	58	**2.5**	*0.20*	90	**3.8**
Primary Energy Supply	**0.7**	**60**	**29.3**	**0.7**	**47**	**22.8**	**0.7**	**37**	**18.2**	**0.7**	**42**	**20.6**
Oil	*0.55*	35	**9.3**	*0.50*	37	**8.9**	*0.45*	6	**1.4**	*0.47*	16	**3.6**
Gas	*0.27*	95	**12.8**	*0.32*	38	**5.9**	*0.30*	47	**7.1**	*0.28*	47	**6.4**
Coal	*0.14*	79	**5.4**	*0.14*	85	**5.7**	*0.17*	76	**6.4**	*0.15*	84	**6.3**
Nuclear	*0.00*	100	**0.0**	*0.00*	100	**0.0**	*0.00*	100	**0.0**	*0.00*	100	**0.0**
Renewables	*0.04*	98	**1.7**	*0.05*	96	**2.2**	*0.06*	97	**3.0**	*0.08*	96	**3.6**
Other	*0.00*	70	**0.1**	*0.00*	75	**0.1**	*0.01*	87	**0.3**	*0.02*	78	**0.7**

Table 2.2 S/D Index Summary Results

2.6 Results - Energy Security in Future Scenario Analysis

Irelands' energy security is in a stage of transition from generally low efficiency, low levels of redundancy and adequacy with reasonably secure primary energy supply, to the reverse. The current trend in Irish infrastructure in general is seen as adequate, with some exceptions in the gas grid. There is increasing efficiencies in both generation of energy supply and consumption in demand, however with decreasingly secure primary energy supply of Oil and Gas. These trends are borne out and parameterised in our analysis of past and future energy systems using the ECN supply demand index. When considering the future of Irish energy security it is important to realise Irish energy security currently remains a function of UK energy security. UK Department of Energy and Climate Change (DECC) policy decisions could have as significant ramifications as Irish Department of Communications, Energy and Natural Resources, or Commission for energy regulation (CER) policy decisions.

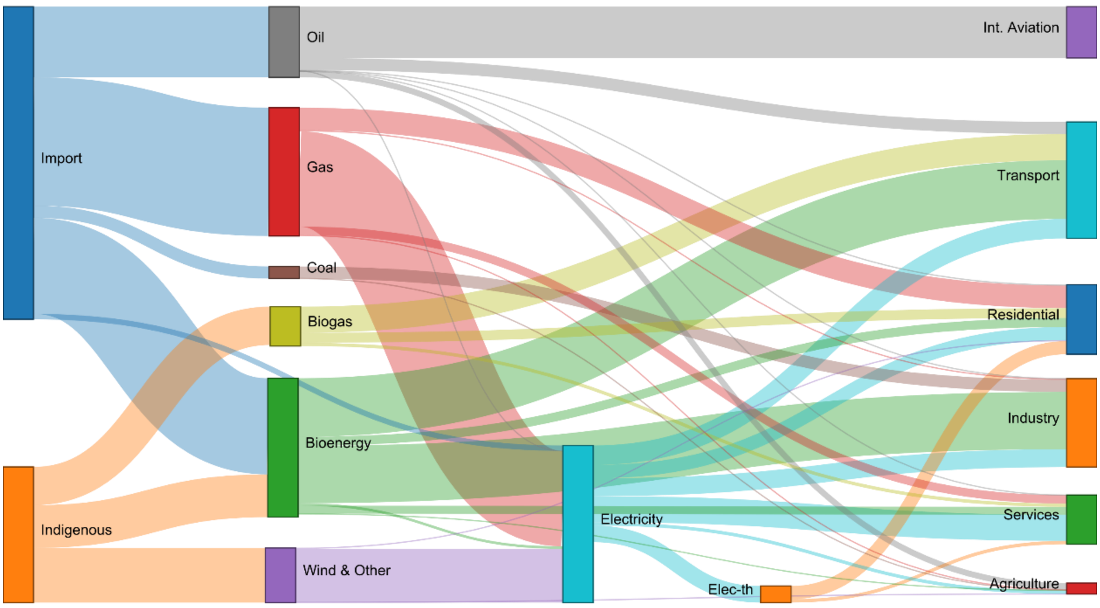

Figure 2.19 Irish TIMES Energy System in 2050 for 80% reduction in CO2 emissions relative to 1990

Figure 2.20 below shows the summary results from a future scenario analysis of the Irish-TIMES energy system with a low ambition scenario of €40/tCO_2 in 2030. The Irish TIMES energy system model, is a least cost optimised Irish energy system, originally extracted from the Pan European TIMES (PET36) model, but updated by

UCC (Ó Gallachóir et al., 2013). Starting from the sectoral demand security, increasing security in industry is brought about by stable and low intensity energy consumption per unit of value added compared against EU benchmarks. The residential and tertiary services sectors have lower but reasonable scores with marginal increases in demand security brought about by increased technological efficiencies, lowering energy consumption per household and per value added in the services sector. There are considerable increases in energy security score in the transport demand sector, given expected demand intensity reductions brought by fuel switching in both private and freight transport with greater efficiency in energy consumption per passenger kilometre and per tonne kilometre of freight transported.

On the supply side, primary energy supply, transformation and transportation of energy commodities are considered. The supply of electricity is seen as growing in security and adequacy given expected interconnector capacity, generation capacity expansion, increased generating efficiency, capacity reserve and redundancy above peak load, with minimal transmission congestion on island. The Gas network security remains stable but low primarily as a result of import capacity constraints in relation to peak demand and a lack of short term storage flexibility to meet peak demand. This issue is currently ameliorated by Gas Network Ireland (GNI) line packing strategies. Strategic LNG import facility with flexible storage or a gas interconnector to a UK LNG facility could mitigate this issue. The twinning of the onshore pipeline from Moffatt provides increased redundancy and adequacy but does not overly affect the capacity flexibility issue. Liquid fuels for transport are seen as secure long term, but not for intuitive reasons. The primary reasoning for transport fuels perceived as increasingly secure, is a result of increased efficiency and fuel switching away from conventional petroleum products, to electricity, biofuels and biogas resulting in reduced demand and significant spare refining capacity on Island. This raises the long term question of the profitability and need for Whitegate if the refinery is to have lower utilisation factors long term beyond 2016. Lastly the primary energy supply of Oil and Gas take into account indigenous production as a proportion of final energy consumption including the Corrib gas field, import dependency, trade relationships via long term contracts, and geopolitics outside of the EU. The depletion of the North Sea Oil and Gas has the largest effect of all elements of Irish energy security. Both primary energy supply of Oil and Gas receive decreasing scores in proportion to the depletion rates of the North Sea and the increasing requirements to meet crude oil, natural gas, and refined products from outside of OECD suppliers. Lastly renewables in the medium to long term bring about increases in energy security of primary energy supply as a result of decreasing import dependency, fuel diversification in final consumption, and supplier diversification.

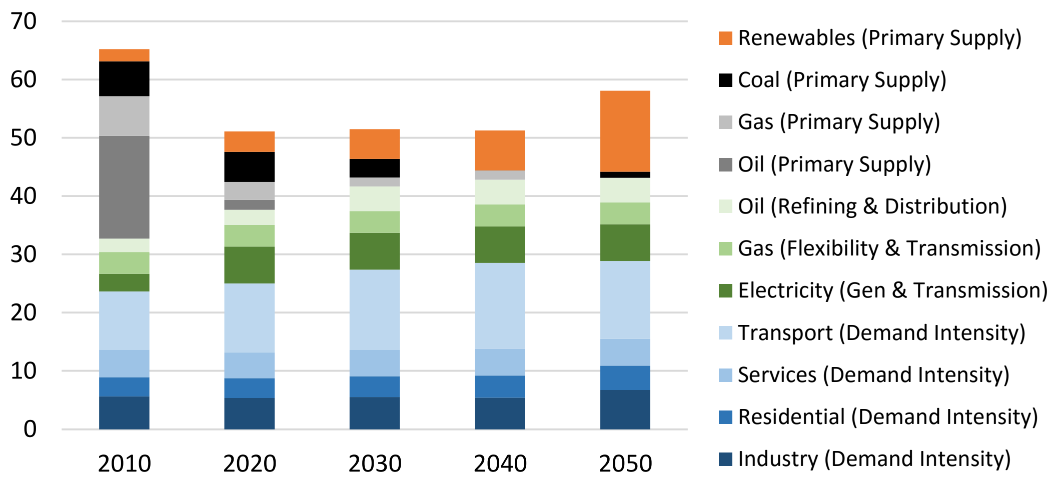

Figure 2.20Energy Security Index Score for a scenario of €40/t in 2030. These chart aggregated energy system optimisation results with a base year from 2005, and so the model results in 2010 differ slightly from the real world statistics in 2010.

The scenario analysis results in Figure 2.21 enable comparison of the security benefits and weaknesses between low and higher decarbonisation ambition policy targets. The results show a rapid drop in energy security between 2010 and 2030 in the business as usual scenario (BAU), given fossil fuel primary energy supply trends away from stable trade partners, and the relatively less demand intensity reductions in the transport sector. This scenario could leave residential heating, freight, and private transport vulnerable to oil price volatility. The low ambition €40t scenario begins to reverse the trend in decreasing security via a combination of transport fuel efficiency, lower demand intensity, and increased renewables in the primary energy supply mix, while still retaining some legacy coal generation. The more ambitions NETS-25% scenario, where there is a 25% green-house-gas emissions reduction in the non-emission trading scheme sector by 2030 relative to 2005 levels, further accelerates the increase in energy security by diversifying away from non-OECD fossil fuels towards indigenous renewable generation, reduced coal generation, with increasing transport efficiency, lower transport demand intensity with its ancillary economic benefits. Longer term to 2050 the higher ambition reduction of emissions has energy security co-benefits in counter acting the trends in decreasing security of primary energy supply, by increases in domestic renewables, efficiency in domestic infrastructure with lower sectoral energy intensity per value added, per household and per unit of freight transported.

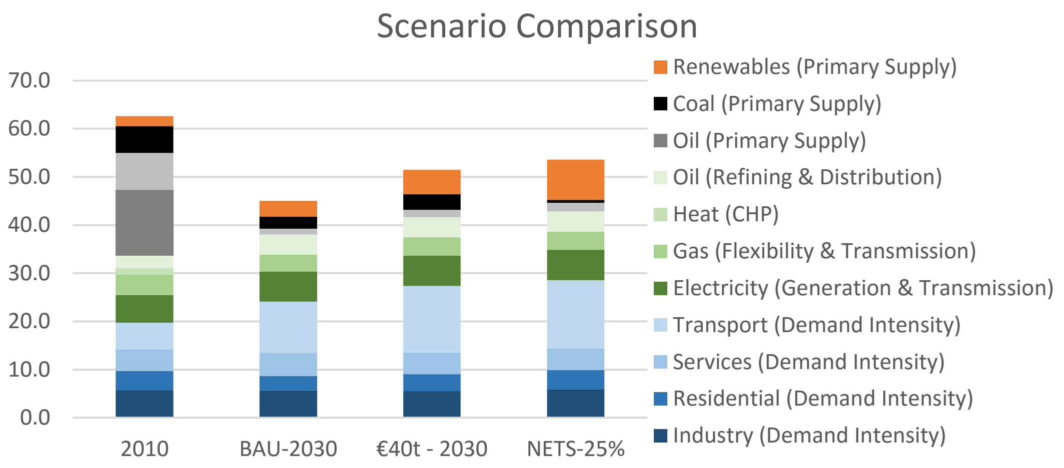

Figure 2.21Energy Security Scenario Analysis in 2030

2.7 Conclusions

The energy security index results show that there are energy security co-benefits in ambitious climate change mitigation policy. The relatively unambitious scenarios analysed showed increasing security as a result of fuel efficiency, fuel diversity, and increased domestic renewable energy production.

The recent energy security literature struggles to formulate a unified non-biased definition of energy security, and outline a multitude of methods of measurement, such as the S/D index outlined here, but also the Hirshman-Herfindahl Index, the Shannon Index for fuel diversity, and many others (Narula and Reddy, 2015). However, many of these index methods do not explicitly take into account the economic cost component of energy security; nor do they include disruptive technological innovation such as unconventional fuel supply in the form of tight oil, shale oil, and shale gas.

This literature review outlines the struggle in perspectives from sovereignty, infrastructural robustness, and market resilience (Cherp and Jewell, 2011), in conjunction with the update assessment of Ireland's energy security. The core among all definitions is the absence of, protection from, or adaptability to threats that are caused by or have impact on the energy supply chain.

The reductionist indicator perspective does not enable the analysis of trade-offs and co-benefits within the energy system to provide resilience between energy system elements. Thus an integrated energy system assessment perspective with the goal of measuring utility and GDP impacts for energy security constraints and shocks are the recommended measurement approach. This is the continued goal throughout this thesis.

However, this recommendation comes with a caveat.

As already discussed, there are many differing rationales with regard to measuring energy security. Primarily they focus on securing fossil fuel primary energy supply. In the light of the COP21 agreement, there may be an inherent instability induced in the global energy system, where conflicting motives for fossil fuel demand destruction, may lead to an oligarchy or cartel driven supply glut, which will reduce fossil fuel prices, reducing the effectiveness of low carbon technology policies, incentives, carbon taxes and make the transition to a low carbon economy more difficult. Low fossil fuel prices, will stimulate the global economy temporarily for a few quarters or 2 years whereby fossil fuel demand recovers inducing fossil fuel price spikes, and economic recession.

The question remains, how you can secure a self-destructive and by design inherently self-stabilising system, to a new equilibrium away from the carbon intensive energy source that enables its security and function. i.e. the long term securing of fossil fuels will destabilise the energy system via climate change. In the low carbon transition, the long term expropriation of resources may create new inequalities, economic hardship, climate injustice, civil unrest, and new energy security risks.

Chapter 3 ENERGY SECURITY ANALYSIS: THE CASE OF CONSTRAINED OIL SUPPLY FOR IRELAND

Primary Output:

Glynn, J., Chiodi, A., Gargiulo, M., Deane, J.P., Bazilian, M., Gallachóir, B.Ó., 2014. Energy Security Analysis: The case of constrained oil supply for Ireland. Energy Policy 66, 312–325. doi:10.1016/j.enpol.2013.11.043

3.1 INTRODUCTION

This paper investigates the optimum, least-cost, energy system for the Republic of Ireland under a range of security of supply scenarios using the Irish TIMES energy system model. Peer reviewed research using this model has to-date focused on the technically feasible, least-cost Irish energy system required to achieve renewable energy targets and green-house-gas mitigation targets from European Directive 2009/28/EC, Directive 2009/29/EC and Decision 2009/406/EC (Chiodi et al., 2013b; Deane et al., 2012; O'Gallachoir et al., 2010a, 2010b, 2012). In contrast, the focus of this work is upon maintaining energy services demand at least cost in the context of energy security scenarios. Irish TIMES is extracted from the Pan European TIMES Model (PET[36]). The TIMES model has also been used previously in European scale energy security scenario modelling for both the SECURE and REACCESS projects (Doukas et al., 2008; Lavagno, 2011). The scenarios considered here investigate the effects of constrained supply, long term price shocks to supply of crude oil, refined crude oil products, and indexed gas prices on the Irish energy system.

3.1.1 IRISH CONTEXT

Ireland currently imports 88% of total primary energy requirement (TPER) while the EU-27 average in 2011 stands at 54%. Oil accounts for 49% of TPER and 59% of Total Final Consumption (TFC) (See Figure 3.1) (Howley et al., 2012). This high import dependency and lack of fuel diversity particularly in residential heating and transport leaves Ireland with increased vulnerability to oil price and supply volatility (Bazillian et al., 2006; Dennehy et al., 2011; Forfas, 2006; Gupta, 2008; Hirsch and Amarach Consulting, 2006; IEA, 2007; O'Leary et al., 2007; Scheepers et al., 2007; Stewart et al., 2008). Ireland's total oil imports are declining on average by 6.6% per year since its peak in 2006 at 202 thousand barrels a day (kb/d). Irish TFC of oil products has declined since 2007 at a rate of -6.28% per year since its peak at 8,592 thousand tonnes of oil equivalent (ktoe) (~168kb/d). Even given declining imports, the nominal costs of net imports of oil rose to €4.07bn in 2011, representing 2.56% of GDP. The stabilisation of the European debt crisis and thus exchange rates in 2012 have seen Irish oil imports drop to €3.6bn, equivalent to 2.26% of GDP. Total fossil fuel imports have declined from €5.55bn (3.49% GDP) in 2011 to €5.19bn (3.22% GDP) in 2012 (See Figure 3.2). The United Kingdom is Ireland's primary supplier of refined oil product historically accounting for over 90% market share, with near 100% market share in 2012. Their crude oil production is declining at 7.6% per year since 1999. Primary UK crude oil suppliers for 2012 are; Norway (47%), Nigeria (12.8%), Russia (12.6%) and North & West Africa (16%). Norway, Ireland's primary supplier of crude oil with 100% market share in 2000, supplied 22.6% of Irish crude oil imports in 2012 with the remaining 77% from non-OECD Algeria, Libya and Nigeria. Norwegian oil production is declining on average at 5.6% since its peak in 2001 and, combined with operation and maintenance outages, 2012 oil production is down 23.7% on 2011 (see Figure 3.3). Declining oil production within European OECD countries, is increasingly forcing Ireland to source crude oil supplies and by proxy, refined product, from geopolitically less stable countries. This increases the probability of detrimental consequences for Irish energy security into the future (International Energy Agency, 2011a; Kruyt et al., 2009; Stewart et al., 2008; Winzer, 2012).

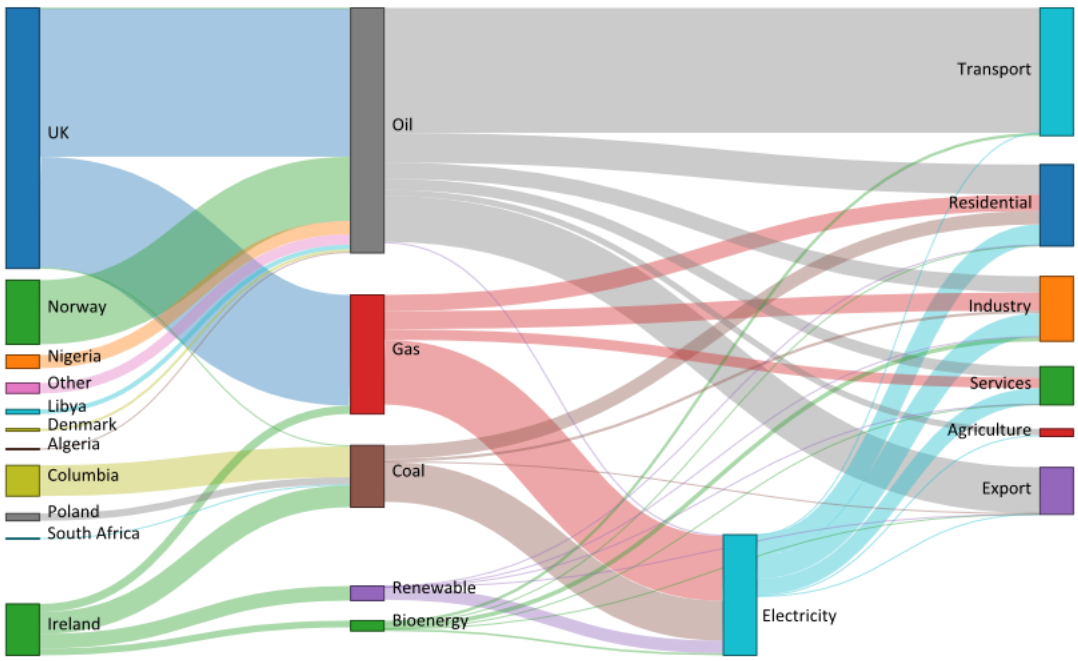

Figure 3.1 Ireland's present energy system energy flow 2011 (Data Source: SEAI, IEA). Primary energy flows from energy sources on the left to sectorial final consumption on the right

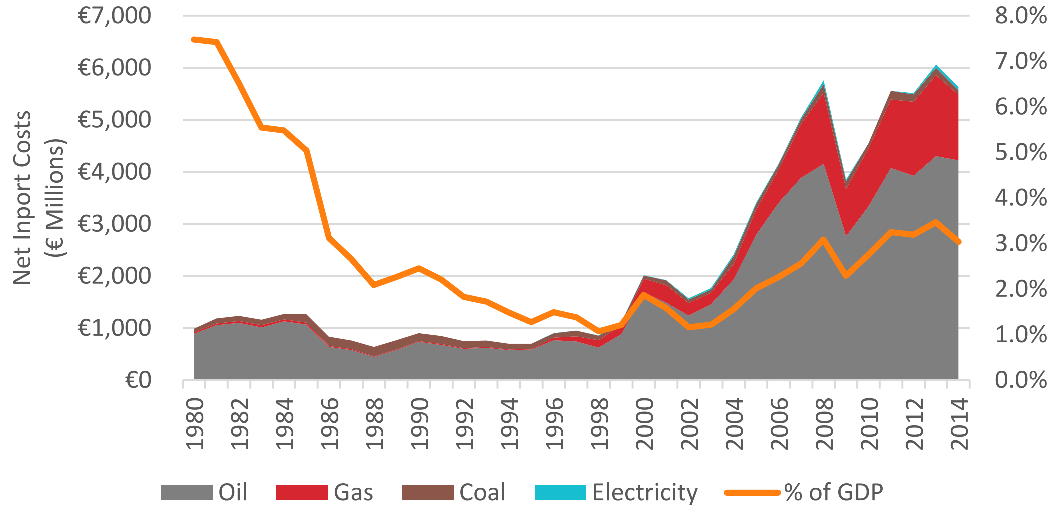

Figure 3.2 Net cost of Irish energy imports (Data Source: CSO, IMF)

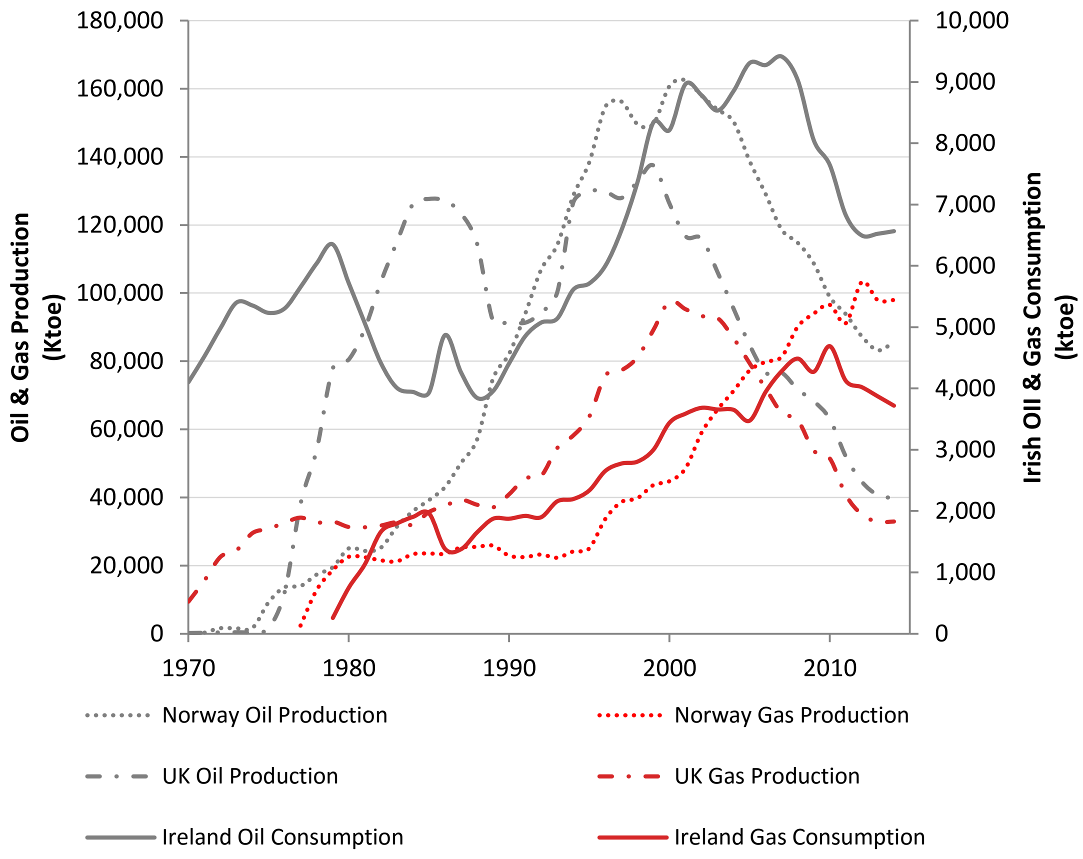

Figure 3.3 Irish oil & gas imports from Norwegian and UK, total oil and gas production

3.1.2 INTERNATIONAL CONTEXT

Global oil production has grown rapidly since the industry inception, at 6% per annum between 1930 – 1965, slowing after the oil shocks of the 70's to a growth rate of 1.8% per year between 1985 - 2003 (Sorrell et al., 2009). The period of 2004 to the 2012 has seen a stagnation of global oil production growth rates. Some assessments to date expect the rate of global oil production to begin to decline within this decade at a rate of between 3% - 5% p.a., in line with the existing producing fields average decline of 6% p.a. (Aleklett et al., 2010; Campbell, 1997; Campbell and Laherrère, 1998; Sorrell et al., 2010a, 2009). The International Energy Agency (IEA) has stated that conventional crude oil production has reached a maximum rate of production, also known as "peak oil", in 2006 (IEA, 2010). However, more recent data has shown marginal increases in conventional oil production above the 2006 peak. Conventional crude oil including lease condensate accounts for 74 mb/d (85%) of a total of 87 mb/d. The IEA outlook anticipates an increasing supply-demand gap to be met by unconventional oil (IEA, 2012). Econometric assessments of the industry's ability to produce at the reduced IEA's future production estimates (IEA, 2008, 1998) are questionable in comparison to bottom up oil field flow rate assessments (Aleklett et al., 2010; Miller, 2011; Sorrell et al., 2010b). Uncertainty in public data makes definitive assessments difficult (Jakobsson et al., 2009). Mean-reverting, trend based econometric oil price forecasting models have tended to underestimate oil prices and their volatility during the recent past (Benes et al., 2012). As a result, oil price volatility and the global economic crisis have concurrently given mixed and conflicting incentives to invest in oil production or renewable energy systems (IEA, 2011).

3.1.3 MOTIVATION AND CHAPTER OUTLINE

The motivation for this work is summarised here. The rate of increase of world oil production has stagnated to a 5 year rolling average of 0.83% in comparison to the historical 1.8% year on year growth as seen in Figure 3.4. This phase of the world oil production profile, commonly referred to as the "bumpy plateau", is expected by some to constrain oil consumption though price induced demand destruction. The rapid depletion of currently producing oil fields in relation to the rate of new production capacity has constrained global spare production capacity. This has considerably decreased the current elasticity between oil price and supply over the past 7 years (See Figure 3.5) and resulted in volatile prices. Sustained high prices have resulted in a 34% nominal increase in annual average euro price for Brent crude oil in 2012 compared to 2008 (See Table 3.1). These price fluctuations have had knock on consequences for indexed gas prices, coal prices and electricity prices. In turn, new correlations between US unconventional gas and international coal production increasingly used in European electricity generation have developed. Lastly, total Irish oil imports are declining at -6.45% per year from 2007 to 2011, accelerating in 2011 to a decline of 10.5% on 2010. UK and Norwegian oil production are also both rapidly declining. Therefore, the following techno-economic scenario analysis aims to investigate and gain insight into the effect of a range of oil and gas, supply and price constraints, on the Irish Energy System.

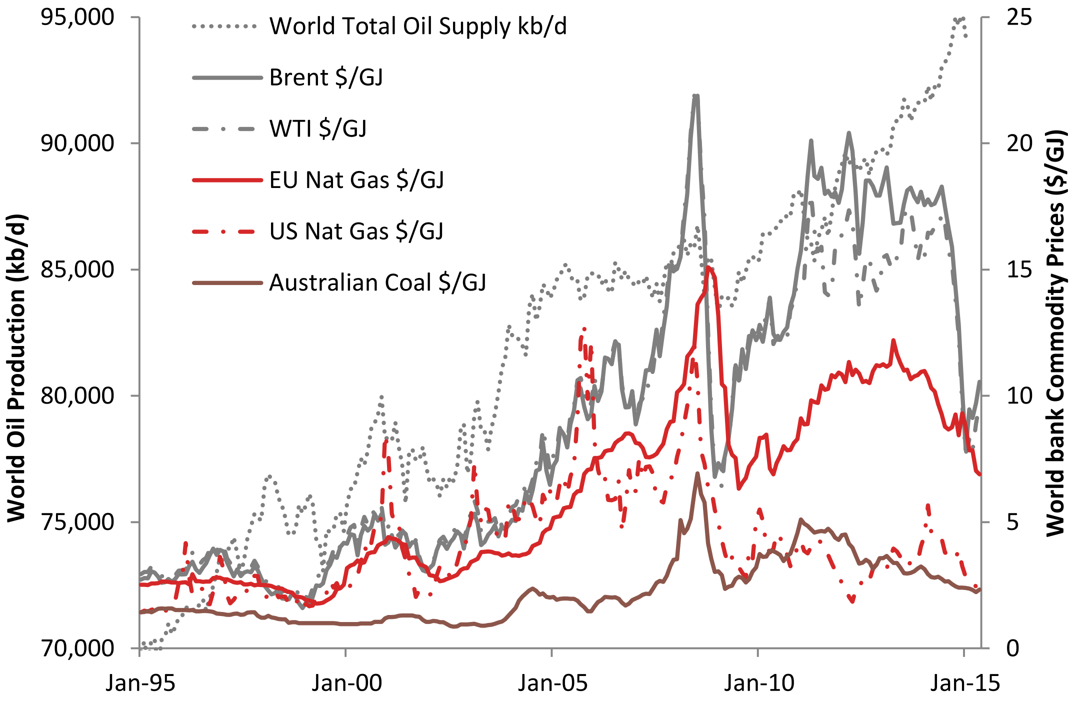

Figure 3.4 European and US commodity prices and world crude oil production

(Data Source: EIA, EUROSTAT, IEA and World Bank)

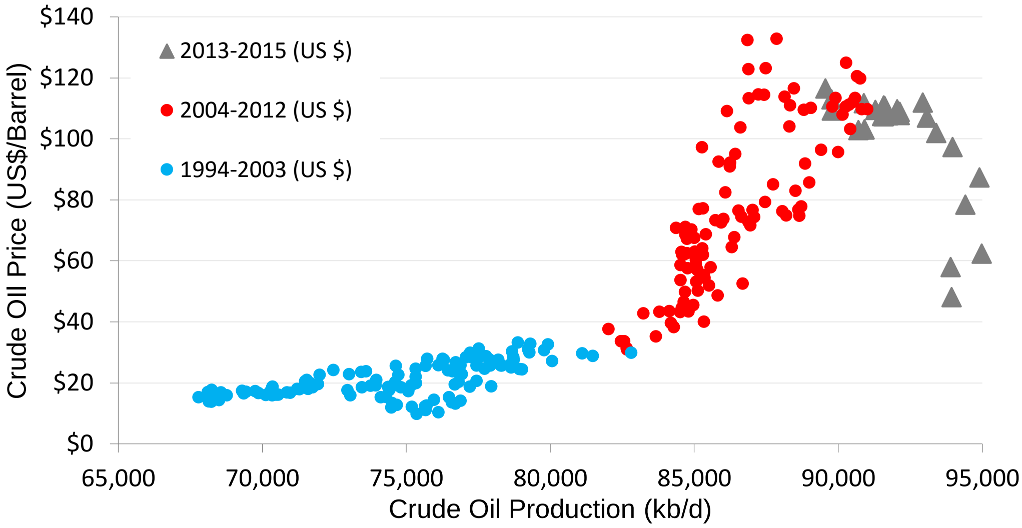

Figure 3.5 Monthly World oil production and price (Data Source: EIA)

Annual Avg. Price	2007	2008	2009	2010	2011	2012	Δ% 2008
WTI ($/bl)	$72.32	$99.57	$61.65	$79.40	$94.87	$94.68	-4.91%
BRENT ($/bl)	$72.47	$96.85	$61.49	$79.51	$111.26	$111.85	15.49%
BRENT (€/bl)	€52.63	€64.93	€43.82	€59.99	€79.92	€87.10	34.15%

Table 3.1 Recent Oil price history US dollars and Euro denominated (Data Source: EIA, EUROSTAT)

3.2 Methodology

3.2.1 *TIMES – Model foundations*

TIMES (The Integrated MARKAL-EFOM System) and its forebear MARKAL, form the primary constituent parts of a family of linear programming models that are broadly used across 177 institutions in 69 countries, supported by the Energy Technology Systems Analysis Programme (ETSAP) under an implementing agreement of the IEA. The model is continually developed, and regional model results are communicated at international bi-annual community dedicated workshops.

TIMES is a techno-economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy system, but may also be applied to detailed studies of individual sectors (e.g. the electricity sector or transport sector). TIMES computes a time varying inter-temporal partial equilibrium on inter-regional energy markets.

The objective function maximizes total surplus. This is equivalent to minimizing the discounted total energy system cost while respecting environmental, technical, and scenario constraints. This system cost includes investment costs, operation and maintenance costs, cost of imported fuels, less the income from exported fuels, the terminal values, and salvage value of technologies at the end of the horizon. The technical foundations of MARKAL models are outlined in Fishbone and Abilock (Fishbone and Abilock, 1981) while the full updated technical documentation of TIMES is hosted online with the ETSAP group (Loulou et al., 2005).

3.2.2 Modelling with Irish-TIMES - calibration and assumptions

The tool used to carry out this analysis is the Irish TIMES model. In its original incarnation, Irish TIMES operated as a component of the Pan European TIMES (PET[36]) project, which included datasets for EU27, Iceland, Norway, Switzerland and the Balkan Countries. The Irish TIMES dataset was extracted, updated with local detailed data, recent macroeconomic projections, calibrated to the national energy system, scrutinised to assure confidence in model assumptions, and peer reviewed (Bergin et al., 2010; Chiodi, 2010; O'Gallachoir et al., 2010b). This work was carried out by the Energy Policy and Modelling Group (EPMG) at the University College Cork (UCC), with macroeconomic projections provided by with the Economic and Social Research Institute (ESRI). Model calibration runs were carried out to ensure acceptably smooth model dynamics, within a range of acceptable rates of change across public policy and private stakeholder expectations. Irish TIMES is developed with a remit to project national energy consumption and green-house-gas emissions to inform national policy decisions funded by the Environmental Protection Agency (EPA) (Ó Gallachóir et al., 2013). Scenarios have been developed to the medium term (2020) and long term (2050), investigating the energy system required to meet EU renewable energy targets and emissions reductions targets (Chiodi et al., 2013a, 2013b).

The Irish TIMES technology database contains descriptive time dependant economic and technical data for approximately 1600 supply and demand side energy technologies. The model specification has 12 annual time slices; four seasons, day, night and peak for a time horizon of 45 years from the base year of 2005 to 2050.

While the model is continually updated with physical energy service demand projections derived from macroeconomic drivers, the model version used in this analysis is based on macroeconomic forecasts from the Economic and Social Research Institute in 2010 (Bergin et al., 2010). These demand driver projections utilise the ESRI's in house HERMES model in conjunction with the GEM-E3 model of industry Autonomous Energy Efficiency Improvement (AEEI, GEM-E3) (Fitzgerald and Kearney, 2002; Hennessy and FitzGerald, 2011). Primary energy supply commodity prices are based on the 2008 IEA world energy outlook real prices (IEA, 2008). Specific attention has been paid in calibrating national technically feasible renewable energy resource availability and costs for onshore and offshore wind, wave, tidal, hydro, solar and bioenergy technologies (Chiodi et al., 2013a, 2013b; Deane et al., 2012).

At its most basic the model can be thought of as the reference energy system constituent parts calibrated to the Irish energy system in the base year; namely the available energy resources, their costs of extraction or trade, their transformation into end use fuels that supply sectoral energy service demand (See Figure 3.6). The model calculates a least cost energy system, where least cost optimum technology choices for a specific set of scenario constraints and assumptions are the primary output. The total energy system characteristics can be interrogated to calculate other outputs including, primary energy requirements, refinery and electricity generation fuel mixes, final energy consumption by fuel type, environmental emissions, total system costs, investment costs, commodity prices and their rates of change over the model horizon.

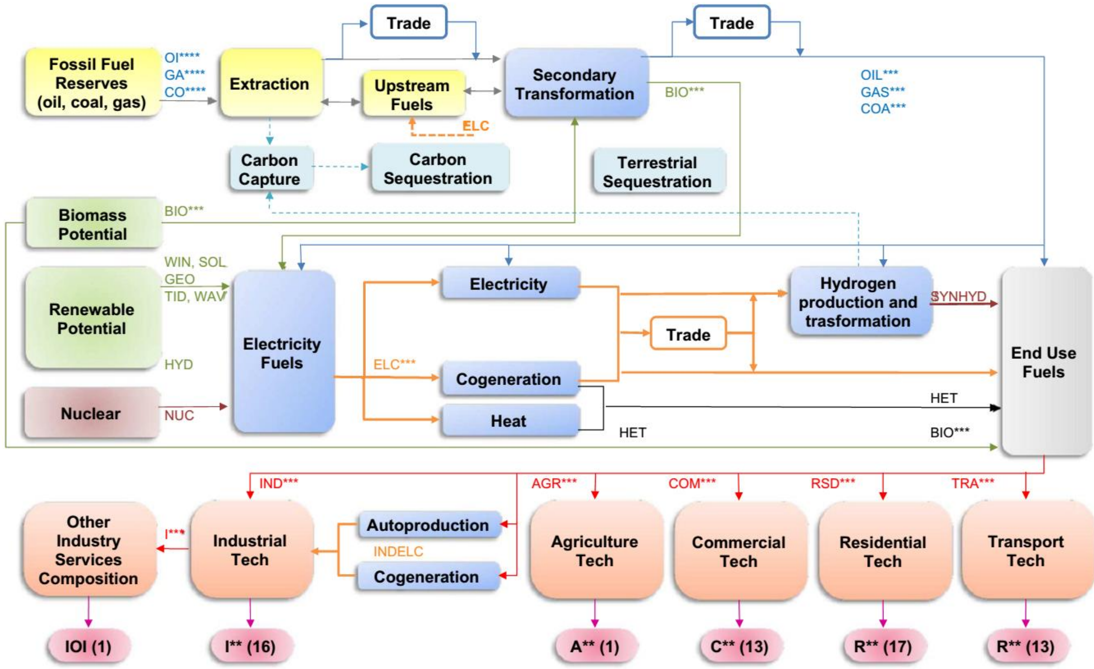

Figure 3.6 The Irish-TIMES Reference Energy System (Gargiulo et al., 2010)

At a more technical level of the formulation of the mathematical model, 60 sectoral energy service demands (ESD) are linearly calculated as the product of sector specific exogenous macroeconomic demand driver (DDR) variables (GDP, Value Added, household numbers etc.) and time dependant coefficients for each ESD in Irish-TIMES. These drivers project the growth from the base year ESD which are technical characteristics of the base year calibration of the model technologies. These ESD are physical requirements, such as tonnes of cement, tonnes of aluminium, tonne-kilometres of freight to be moved, passenger-kilometres of people to move, electricity demands, residential heating and cooking thermal energy demand etc. The ESD are technology independent in that multiple technology choices can meet each demand (A full list is available in (Chiodi et al., 2013b; Ó Gallachóir et al., 2013)). The number of ESD reflects the diversity of demands in each sector, and the complexity of some sectors in comparison to others, for example the residential sector has 17 ESD against agricultures 1 ESD. The model then optimises the objective function for least total system cost, giving the technology and commodity choices to meet these ESD, instantaneously across all sectors. This assumes perfect information and perfect foresight of macroeconomic conditions and energy service demands. The energy service demands in this study are inelastic to price. The key variables that this paper investigates is the supply side input component of oil and gas trade and their prices.

3.2.3 *International Monetary Fund supply scenario inputs*

The scenario inputs specific to this paper are based on recent work within the research department of the International Monetary Fund (IMF). The IMF first published oil sector research using their Global Integrated Monetary and Fiscal model (GIMF) in a chapter titled, "Oil Scarcity, Growth, and Global Imbalances", within their 2011 World Economic Outlook (International Monetary Fund, 2011). The model investigates the effects of oil supply, price, substitutability and oil derived productivity upon the global and regional economies. They developed four scenarios, a benchmark (IMF1), an upside efficiency scenario (IMF2) with greater substitution away from oil, a downside productivity scenario (IMF3) where oil has a greater role in economic production and a downside scenario (IMF4) where there is a greater decline in oil production.

The benchmark scenario considered the effect of a slowing of the growth rate of global oil production, where it increases only at 0.8% p.a. in comparison to the historical 1.8% p.a. This knowledge is reflected in market realisation future supply will not automatically meet demand as has been historically assumed. This results in an immediate price shock up 63%, reflecting the relatively small, short term price elasticity. Demand destruction and comparably larger medium term price elasticities enable fuel substitution, and the stabilisation of the rate of price increase by year 3 on a new higher long term price trajectory. An upside efficiency scenario investigates the effect of greater technological substitutability away from oil. A productivity scenario derived from the work of Ayres, Warr and Kümmel (Ayres et al., 2007, 2003; Ayres and Warr, 2010, 2005; Kümmel, 2011; Kümmel et al., 2010, 1985) investigates benchmark substitutability but included increased levels of productivity and cost share of oil up from historical 5% to 25% of cost share of production. The IMF considered a final fourth scenario of equivalent substitutability of the benchmark scenario, but where global oil supply declines at 3.8% in comparison to the benchmark, or 2% in gross terms. This effect again takes the shape of a market realisation of declining oil production at 2% per annum, and an immediate price spike of 240% in year one. Medium term fuel substitution leads to a slowing of the rate of price increase by year 3 at a 286% real price increase, growing to 487% real price increase by year 10. This "peak" scenario (IMF4) and the benchmark (IMF1) scenario results show world oil supply and resultant price increases of 350% and 90% respectively within 5 years, and are outlined in Figure 3.7. While these outputs may appear divergent and extreme, they are based on conservative assumptions of maintaining a 0.8% growth in oil production to a gross 2% oil production decline rate, while others expect decline rates of between 3% - 5% (Höök et al., 2009; Robelius, 2007; Sorrell et al., 2010a). The Benchmark and Peak scenario IMF outputs are the starting point for this paper's investigation, and while the Irish TIMES model is calibrated to the current Irish energy system, the outputs should be seen as exploratory scenarios rather than forecasts given macroeconomic uncertainty.

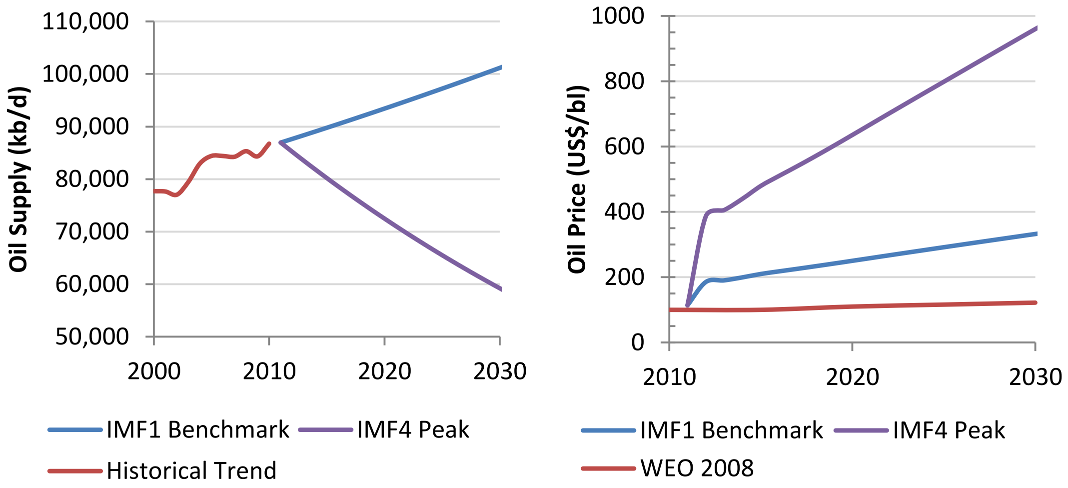

Figure 3.7 IMF - GIMF model outputs – Extrapolated World oil supply and resultant prices

3.2.4 Scenario Description

The data rich nature of this modelling enables a multitude of possible scenarios to be generated. The approach in this paper develops sequentially from each scenario, to enable clear and concise scenario comparison. Five scenarios are presented, with the main focus on increased oil price scenarios. The Reference energy system (REF) scenario provides the base case calibrated to the base year (2005) energy system which calculates a least cost scenario energy system with current policy against which the remaining scenarios are compared. The remaining scenarios are based on oil import volume constraints of 0.8% annual gross import growth (Vol +0.8%), a 2% annual gross reduction in oil imports (Vol-2.0%), price scenarios using the growth indices of the IMF Benchmark scenario (Costs-Bench), the downside (IMF4) scenario (Costs-Peak), and the final scenario is a combination of the IMF benchmark scenario with an indexed gas price (Bench +gas).

3.2.4.1 REF

The reference scenario (REF) energy system is the least cost optimal energy system development pathway. The base year (2005) and near term development is calibrated against national energy forecasts aiming to include recently implemented policy (Walker et al., 2009). The electricity generation plant mix, the car stock and the housing stock, and overall energy system are calibrated to the existing service demand trends. Commodity price trends continue as per the world energy outlook (IEA, 2008). The reference scenario solution is an ideal least cost optimum pathway from the present energy system, given perfect foresight of future market conditions, without any additional constraints. However, the reference scenario is not a long term expected outcome as such as it is an optimised solution; rather, it is a counterfactual benchmark against which alternative scenarios can be compared. In the reference case, it can be assumed there is a general equilibrium between prices and demands in the calibration energy service demands. General equilibrium cannot be assumed between the shock scenarios arising from the GIMF scenarios and the results in the Irish TIMES model. The is not an equilibrium between prices from GIMF and the demands in Irish TIMES. This problem is often an issue in partial equilibrium least cost optimisation models and hence the reason that macroeconomic feedback is such a critical element of research. This is addressed in later chapters of the thesis.

3.2.4.2 VOL +0.8%

The “Vol 0.8%” scenario places an upper bound of 0.8% gross annual growth on the import capacity of crude oil and crude refined product, in proportion to the baseline amounts of each commodity required in the reference case. This constraint begins in 2011. This scenario investigates purely the volume constraint component of the IMF1 benchmark case. The aim is to introduce a long term continued tightening of world oil supply, while production growth is still maintained. The scenario is hypothetical in nature to explore the extent of change in the energy system given a policy of oil import volume constraint.

3.2.4.3 Vol -2%

The "Vol -2%" scenario places an upper bound of -2% gross annual decline on the import capacity of required crude oil and refined product in proportion to the baseline amounts required of each commodity in the reference case. This constraint begins in 2011. The aim here is to create a situation whereby national oil imports are constrained in line with a global oil supply contraction. This scenario is also hypothetical in nature, to explore the extent of a more extreme change in the energy system given a policy of oil import volume constraint.

3.2.4.4 Costs-Bench

The "Costs-Bench" scenario replaces the reference scenario oil commodity prices, with oil commodity prices derived from the reference case prices adjusted for the IMF1 Benchmark price percentage changes. Both the Reference energy system prices and the IMF percentage price changes are in real terms in year 2000 euro. This scenario utilises a price signal to explore the effects of a continued slowing in the growth rate of global oil production. Similarly, the price constraints also begin in 2011.

The benchmark scenario can be considered as the case where oil prices continue to rise, but where natural gas becomes a global fungible commodity and through arbitrage and LNG trade, gas price indexation to oil price ceases to be practiced. Thus gas prices remain unchanged even with increasing oil prices.

3.2.4.5 Costs-Peak

The "Costs-Peak" scenario, similar to "Costs-Bench", updates the Irish TIMES commodity price database with prices congruent with the IMF4 downside Peak scenario. Again, this scenario utilises a price signal to analyse the effect of a global contraction of 2% in oil supply.

The IMF scenario inputs and outputs are based on linear trends and are extrapolated from the original 2030 IMF model horizon to the Irish TIMES 2050 horizon. The volume scenarios only constrain imports volumes, while cost scenarios only constrain commodity prices. All other variables remain the same as the reference energy system

3.2.4.6 Bench +Gas

The final "Bench +Gas" costs scenario updates the "Costs-Bench" scenario prices with a gas price indexed to the IMF benchmark oil prices at an elasticity of 0.69, based on a historical linear regression. Similar to the "Costs-Bench" scenario, a price signal is used to explore the likelihood of limits to smooth substitutability of natural gas.

This scenario is counter intuitive to the common perception of a global gas glut. The logic follows that, while the shale gas revolution in the US has caused the US gas price to collapse, European gas prices have not. Fungible LNG deliveries have not abated cost of the slow pace of unconventional gas development policy in Europe. Resultantly, European gas prices remain indexed to oil price, and rise congruently.

3.3 Results

3.3.1 Reference energy System 2020 – 2050

The reference energy system solution for 2020 visualised in Figure 3.8 is not dissimilar to the current energy system seen in Figure 3.1. The economy returns to GDP growth averaging 1.8% over the period of 2005–2020 and 1.69% to 2050. This is an exogenous driver across all scenarios. National renewable energy and energy efficiency targets see growth in renewables, predominately wind powered electricity generation. Natural gas replaces coal in the electricity generation mix. The transport sector sees growth in biofuel consumption but remains dominated by oil products. Following from national renewable energy policy, each sector sees the contribution of renewable energy grow as a proportion of final energy consumption. The horizon of 2020 - 2050 sees similar trends continue with the exception of a return of coal in the electricity generation mix beyond 2020. Natural Gas begins to play a considerable role in the transport sector by 2050, with slow renewables growth.

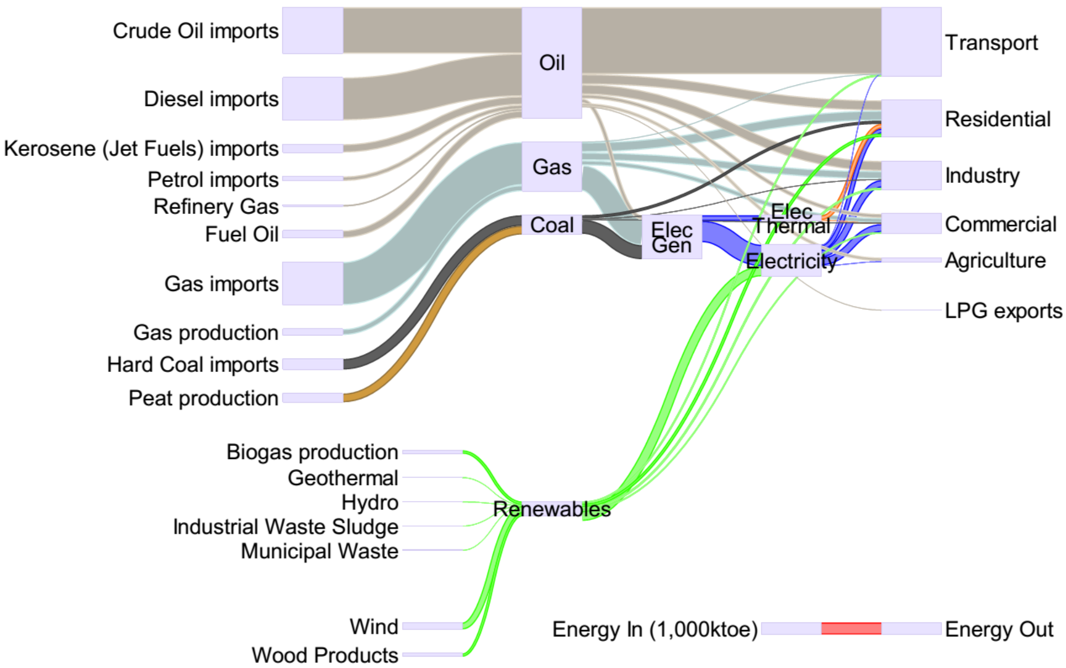

Figure 3.8 Reference Energy System 2020

3.3.2 OIL IMPORT VOLUME CONSTRAINED SCENARIO

The first set of scenarios focusing on volumetric import constraints, show a reduction in TFC of oil products in line with the 0.8% annual growth and 2% annual decline bounding constraints. The 0.8% growth scenario does not show any technology change in comparison to the reference scenario. This indicates that this scenario does not constrain the energy system. The reference case least cost energy system indicates a 27% reduction in oil consumption over the period of 2010 to 2050 or an annual decline of -0.62%, irrespective of the +0.8% annual growth constraint (See Figure 3.9).

The PEAK (2% decline) scenario shows a 62.7% relative decline in oil consumption from a reference TFC of 54.3% to 20.1% over the model horizon from 2010 to 2050. This is equivalent to a -2.3% annual decline rate in oil consumption. The transport and industry sectors are the only sectors to exhibit a considerable technological shift in comparison to the reference case, toward gas substitution for industrial thermal processes, compressed natural gas vehicles, biofuels and electric vehicles (See Figure 3.10). The natural gas component of TFC grows by 245% or 2.7% per annum from 2010 to 2050. Technological efficiencies from fuel switching in the transport sector account for the majority of a 2.6% reduction in TFC by 2050 (See Figure 3.9 & Figure 3.10). These oil import volume constrained scenarios form the basis for comparison against the more detailed price signal effects in the following section.

At this stage it should be highlighted again that volumetric constraints used in these scenarios are not a realistic real world scenario, as they do not reflect price rises that would inevitably result in constrained global oil supply. However, it is useful in later discussion to isolate the effects of volumetric constraints and price constraints on the energy system.

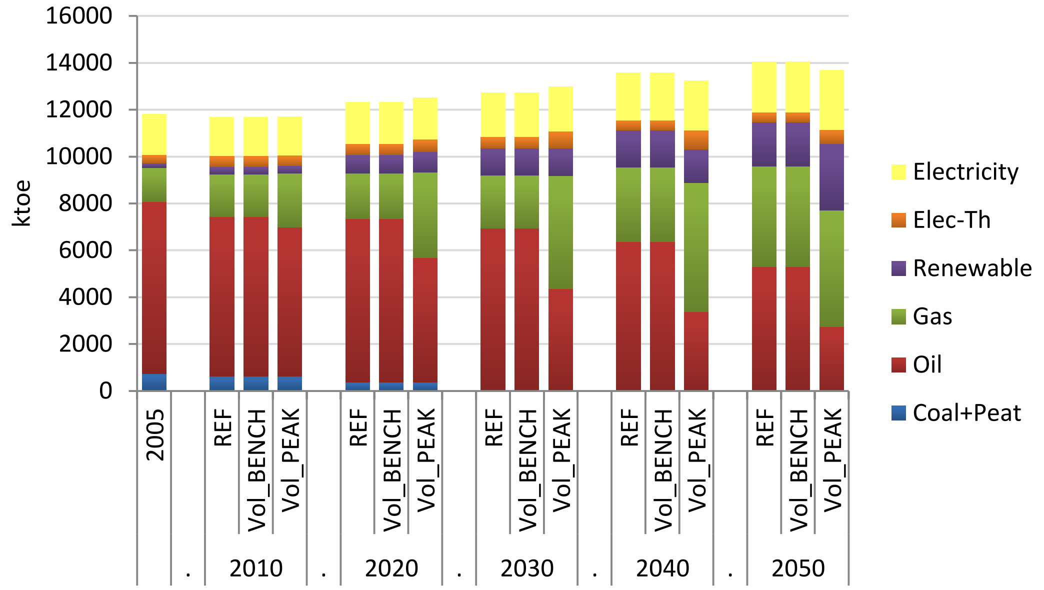

Figure 3.9 Total final energy consumption by fuel for oil import volume constrained scenarios

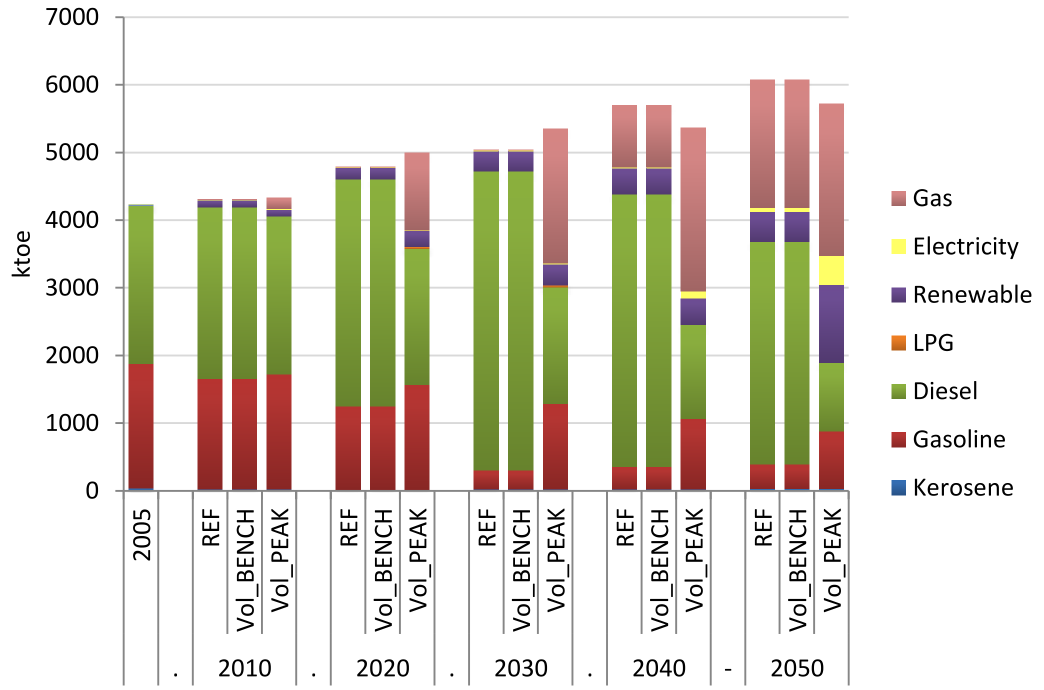

Figure 3.10 Total final energy consumption in the transport sector for oil import volume constrained scenarios

3.3.3 OIL PRICE CONSTRAINED SCENARIO

The increased price constraint scenarios show more considerable changes in the final energy balance in comparison to the volume constrained scenarios (See Figure 3.11). Oil consumption drops to 10.7% and 7.3% respectively as a percentage of TFC, for the benchmark and peak price scenarios by 2020. This indicates a radical shift in the optimum energy technology choices and the impact of the price signal is inferred to be much greater when compared to 57% and 42% of TFC for the equivalent volumetric constraints scenarios. The summary statistics for the scenario results are outlined in Table 3.2.

There is evidence of a threshold being met within the model showing technological limits to substitutability away from oil products, even given the significant price differential between the bench and peak scenario prices. Current empirical domestic oil consumption (excluding refined product for export and international aviation) is declining at rates consistent with the benchmark scenario; with a slight time lag. The reduction in consumption in comparison to the calibrated reference case is seen as a result of the contracting Irish economy, reducing domestic oil demand. Irish GDP grew in 2011 at 1.0%, while GNP contracted at -7.1% over the same period. The contrast in effects of import volume constraints and price constraints is clearly illustrated in Figure 3.11.

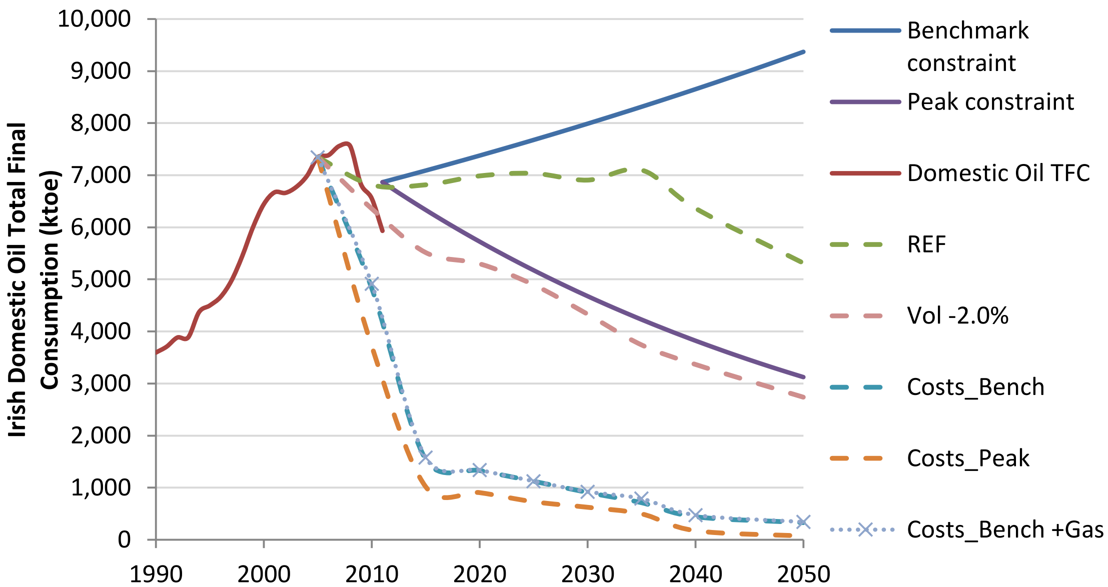

Figure 3.11 Oil final consumption - Scenario comparison with historical domestic oil consumption

The primary summary areas of change in comparison to the reference scenario are seen in a fuel shift towards natural gas, renewable fuels and electricity in both transport and home heating technologies (See Figure 3.12). Natural gas supplants oil as the primary source of energy by 2020 for bench and peak scenarios. Renewable fuels see rapid growth over the model horizon. The renewable fuels used are primarily biodiesel and bioethanol imports for transport use, with biomass in industrial boilers and CHP plant while, biogas is utilised in CNG vehicles, residential space heating and residential water heating. This is seen in greater detail in subsequent results sections. Electrification of thermal processes expands rapidly at up to 2020 substituting oil consumption, and slowing thereafter. Electricity generation for non-thermal processes sees only minor differences across all three scenarios. Fuel and technology switching result in energy savings of 7.8% and only 0.4% of TFC in 2050 comparing the bench and peak scenarios to the reference scenario.

The sector shares of TFC remain reasonably stable throughout the model horizon, with the largest fluctuations taking place in the transport sector where greater fuel efficiencies are gained in technology changes. The summary results of the considerable changes most notably to transport and residential sectors are presented in the following sections.

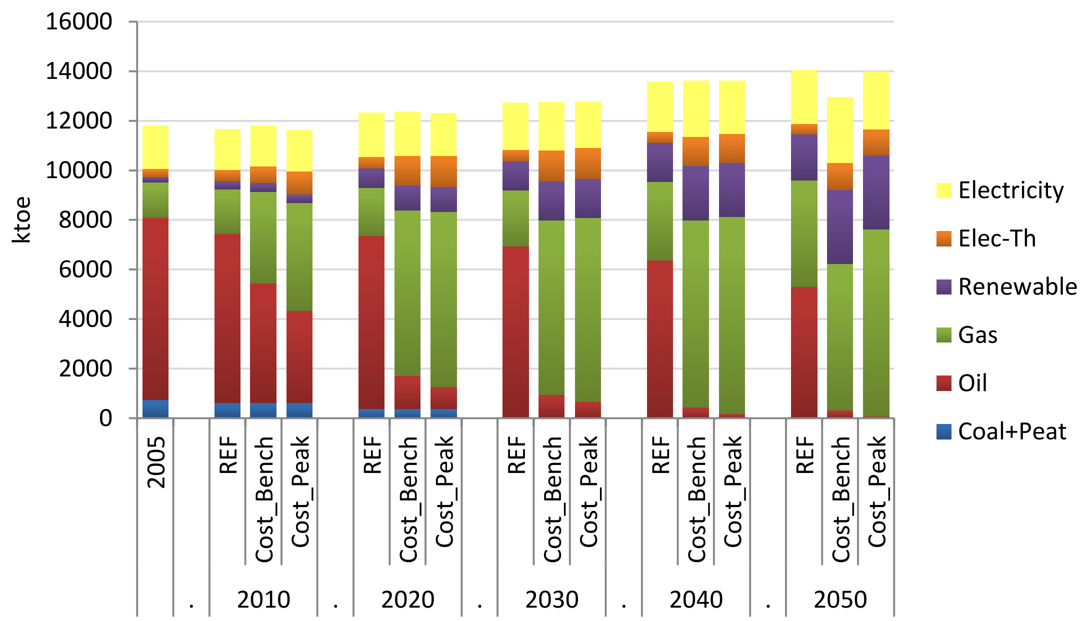

Figure 3.12 Total final energy consumption by fuel for price constraint scenarios

3.3.3.1 RESIDENTIAL SECTOR

The residential sector exhibits an almost complete removal of oil, coal and peat consumption from its energy mix, with rapid substitution towards electrification of space and water heating with supplementary use of biomass and biogas where growth rates of resources and feed stocks allow (See Figure 3.13). Technology changes enable efficiency gains and energy conservation of 2.2% and 2.8% in the bench and peak scenarios by 2050.

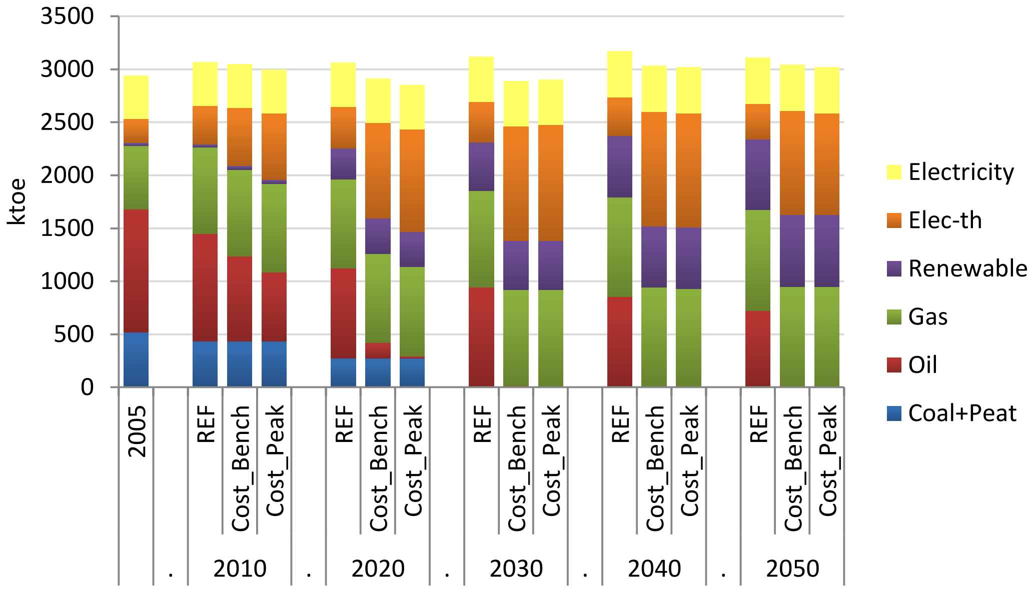

Figure 3.13 Total final energy consumption in the residential sector

3.3.3.2 TRANSPORT SECTOR

The transport sector is the dominant sector in Irish energy balance currently making up approximately 37% of TFC, 98% oil dependent, with 2% of transport energy alternatively derived from biofuels and electricity. The model outputs indicate a considerable and significant shift in fuel consumption mix and technology choices across the model horizon and each scenario. The initial reference reduction in gasoline consumption is followed by a reduction in diesel. Gasoline and diesel make up 26% and 70% respectively of the 2020 reference scenario consumption of the domestic transport sector. In comparison, gasoline and diesel make up 3.5% and 12.1% in both the bench and peak scenarios in 2020. This radical disparity continues throughout the model horizon where gas consumptions accounts for to 76% of consumption in both bench and peak scenarios for 2020 and subsides to 61% & 71% for bench and peak scenarios by 2050. This shift is seen in the introduction of compressed natural gas cars and heavy duty trucks. Renewable biofuels are consumed in the form of biogas in cars and road freight, the blending of biodiesel for train and freight. Minimal electrification continues of small cars, motorcycles and light rail. The use of plug in petrol hybrid vehicles enables greater fuel efficiency gains using minimal levels of petrol in personal car transport in comparison to gas powered personal transport between bench and peak scenarios in 2050.

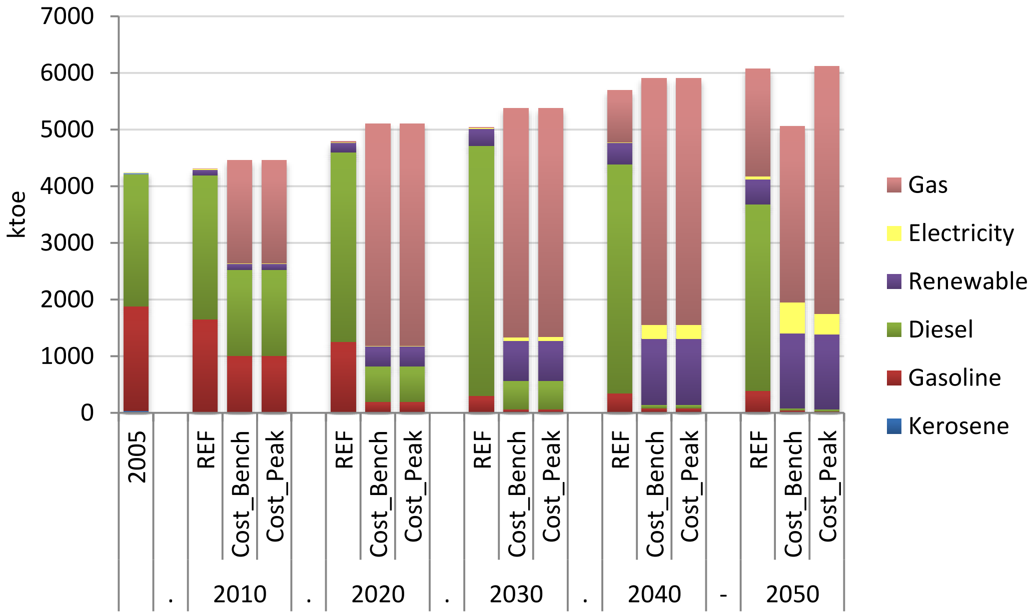

Figure 3.14 Total final consumption in the transport sector

3.3.3.3 Services sector

The services sector exhibits an overall trend of substitution to gas with short term reliance upon electrification of heat with long term use of biomass and biogas (renewables) for space and water heating. However, comparing the reference 2050 scenario with the bench and peak scenarios, a convergence of the energy mix balance is seen. The increased expense of oil drives consumption of electricity for thermal processes to increase in the near term to 2020, with natural gas showing greater growth in the longer term. The electrification of heat brings sectoral efficiency gains of 4.8% and 5.2% TFC in 2020 in comparison to the reference case.

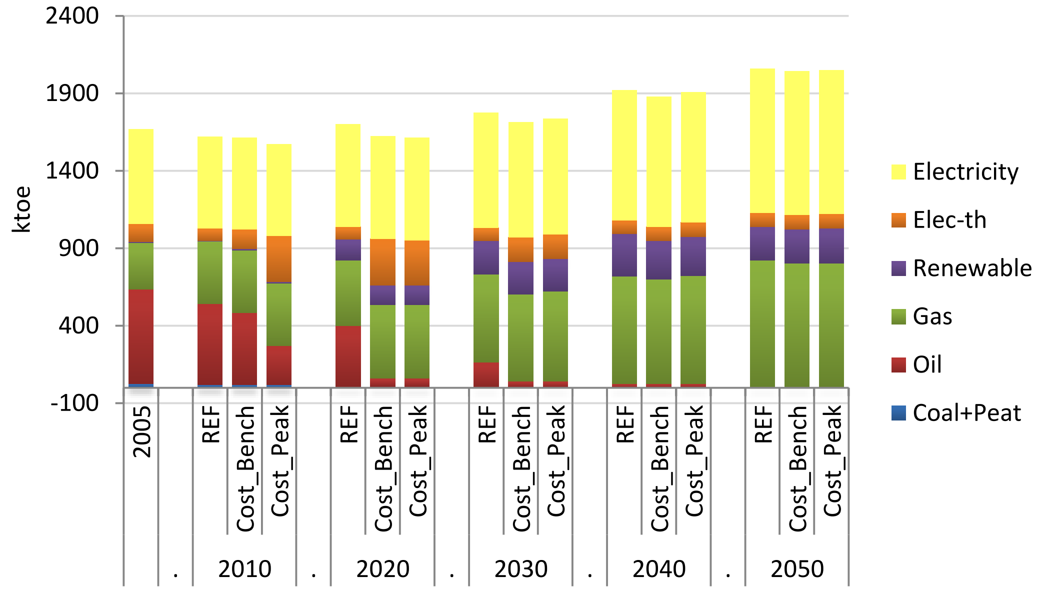

Figure 3.15 Total final energy consumption in the services sector

3.3.3.4 INDUSTRY SECTOR

The Industry sector goes through similar a transition to gas use, with the dominant removal of heavy fuel oil and coal from industrial processes. There is a near 1:1 substitution for gas from oil. The medium term observation of stagnation in the use of bioenergy ceases with the introduction of increased levels of wood products in the renewables mix for thermal processes over the model long term horizon.

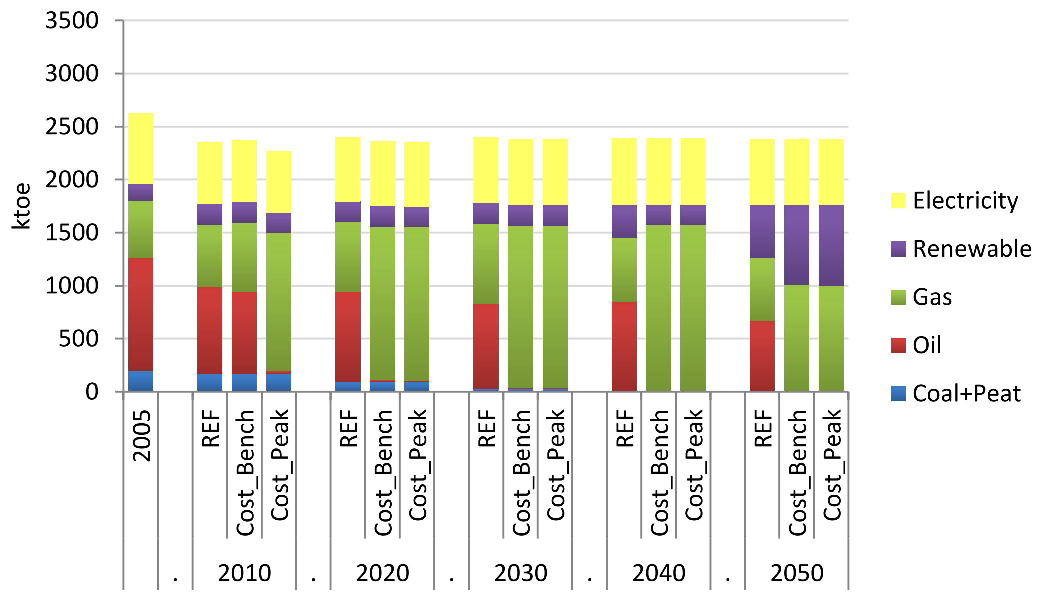

Figure 3.16 Total final consumption in the industry sector

3.3.3.5 *Electricity Generation*

The amount of coal, peat, and oil that the power generation sector can consume is constrained as a result of the current generation portfolio. Thereafter electricity generation is not carbon constrained. 28% and 25.7% growth in electricity generation required in the 2020 bench and peak scenarios comes from an expansion of gas turbine plant, with wind power growing minimally to 572ktoe. The model indicates an expansion of coal fired power generation of primary energy requirement up to 4751 ktoe, 7996 ktoe, and 5779 ktoe, outputting 1995 ktoe, 3358 ktoe, and 2427 ktoe for the reference, bench and peak scenarios. Only the latter two decades leading to 2050 sees further expansion of wind power up to 937 ktoe, 771 ktoe, and 1198 ktoe for the reference, bench, and peak scenarios (See Figure 3.17). The long term also sees increased levels of electricity export via interconnector to the UK.

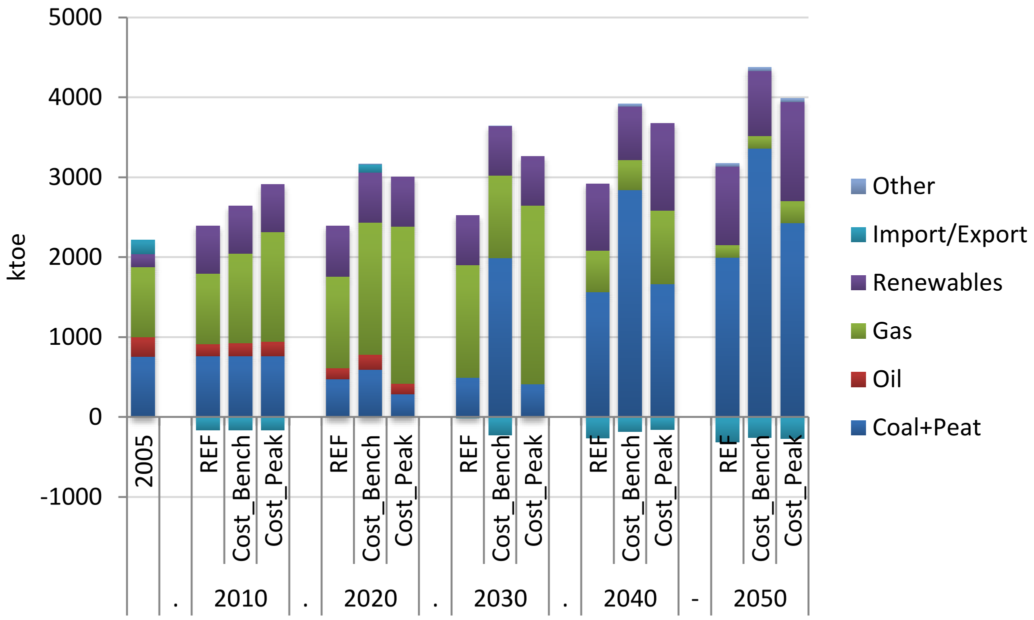

Figure 3.17 Electricity generation by primary fuel source

The electricity consumption per sector is outlined below in Figure 3.18, again summarising the changing picture from the reference case. The expansion of electrical space and water heating in the residential sector is most notable with a short term growth for the bench and peak scenarios to 2020. In the long term post

2030 electrification of the personal car fleet begins installing plugin hybrid and pure electric vehicles in the transport sector.

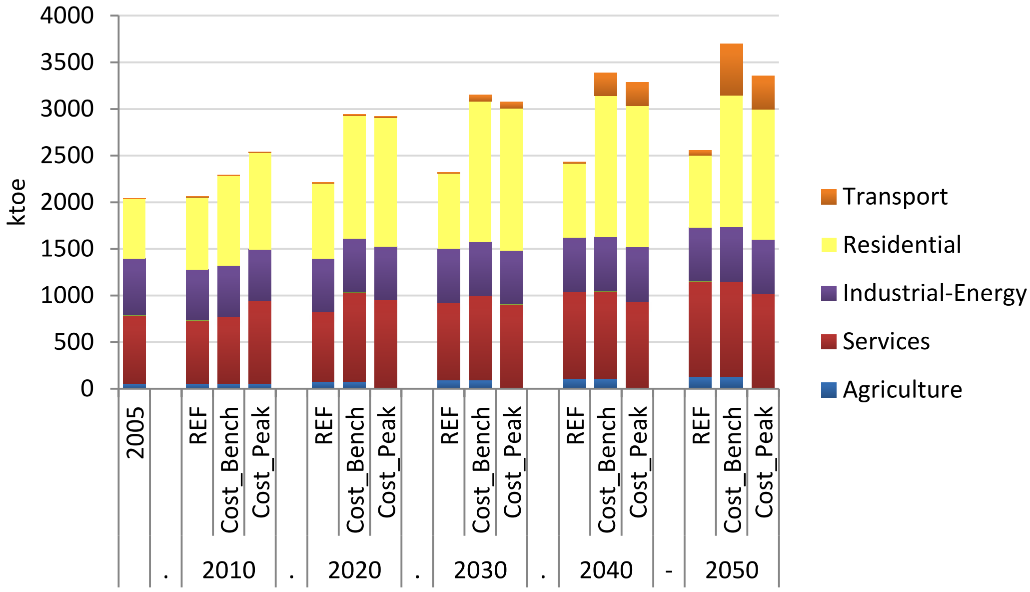

Figure 3.18 Electricity consumption per sector

3.3.4 Oil and Gas Price Constrained Scenario

The bench +gas scenario, representative of gas prices remaining indexed to benchmark oil prices, shows another divergent system scenario from the reference case. Gas remains a transition fuel growing as a proportion of TFC to 2020, but declining thereafter. Renewables grows to 2050 becoming the dominant energy carriers in the transport and industry sectors, with electricity including thermal processes accounting for an increased share of TFC in comparison to the bench scenario.

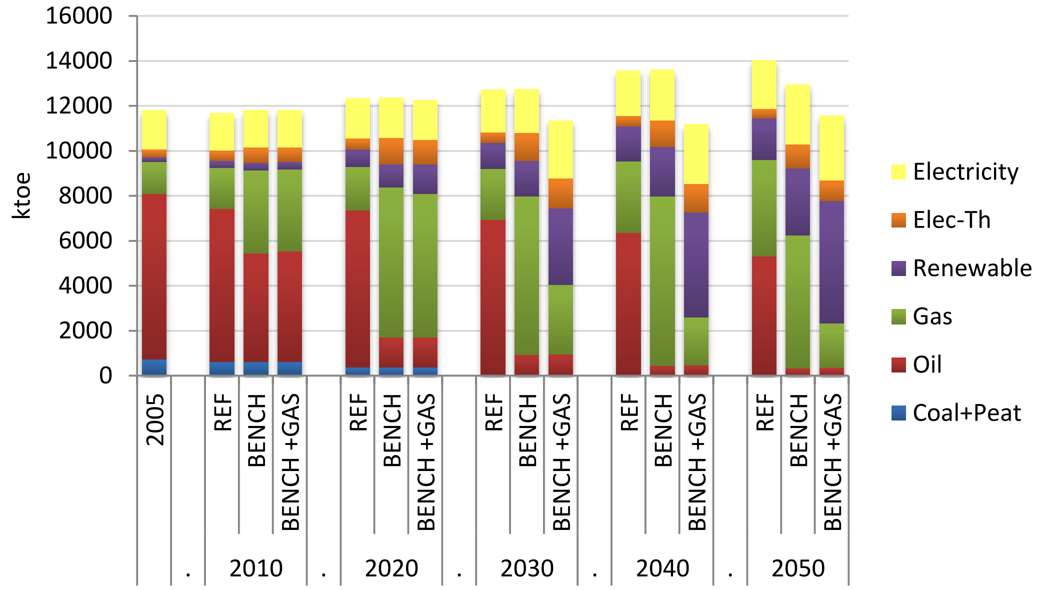

Figure 3.19 Total Final Energy Consumption by Fuel

3.3.4.1 Residential Sector

The residential sector only experiences additional change in a reduction in the use of electrical radiators and additional use of air source heat pumps with electrical boilers. This causes an efficiency gain of 7% over the sector's reference TFC.

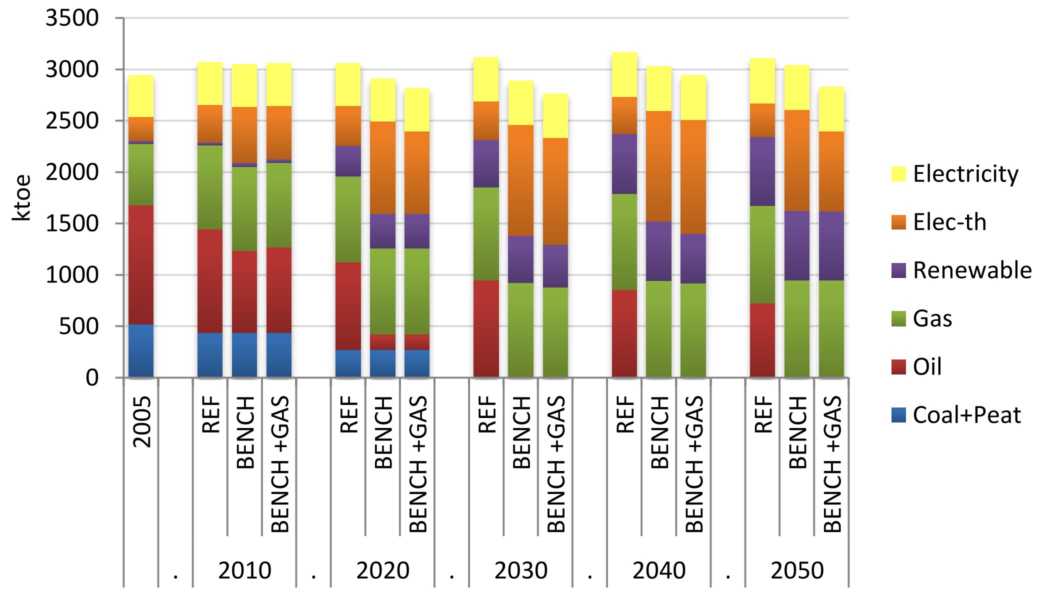

Figure 3.20 Residential Sector Total Final Energy Consumption

3.3.4.2 TRANSPORT SECTOR

The transport sector uses natural gas as a transition fuel in the medium term showing little difference in the sector's energy balance between cost-bench and bench +gas scenarios to 2020. A greater substitution of renewables takes place by 2050, whereby gas consumption is replaced with electric and biofuel vehicles growth. These vehicles enable a fuel efficiency gain of 34.8% in comparison to the 2050 reference case.

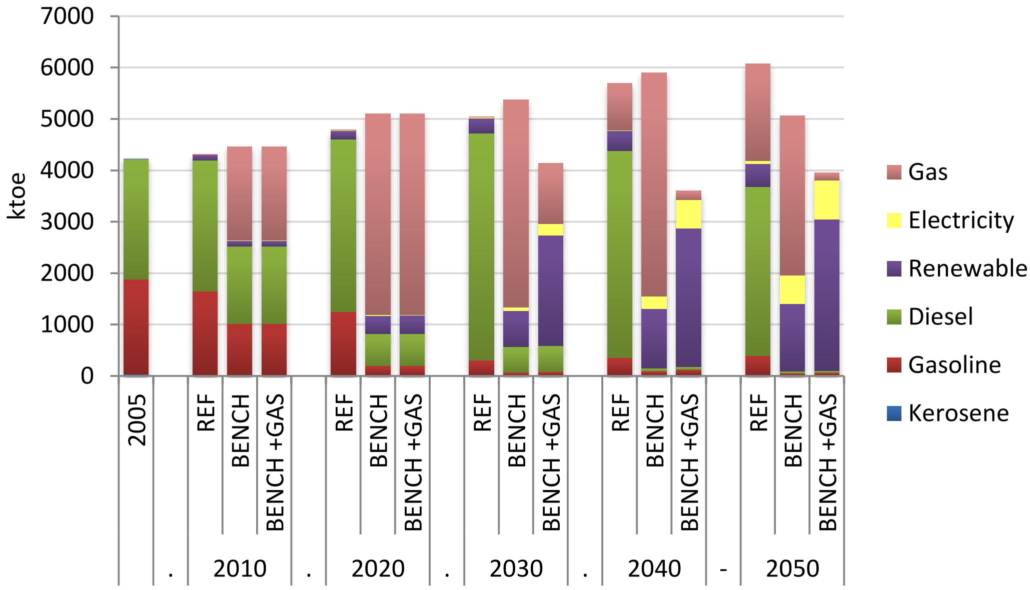

Figure 3.21 Transport Sector Total Final Energy Consumption

3.3.4.3 SERVICES SECTOR

The services sector exhibits a longer temporary utilisation of electrical thermal processes for the bench +gas scenario in 2030 compared to the bench scenario. Gas consumption declines by 2050, with the difference made up by increases in renewables and thermal electricity.

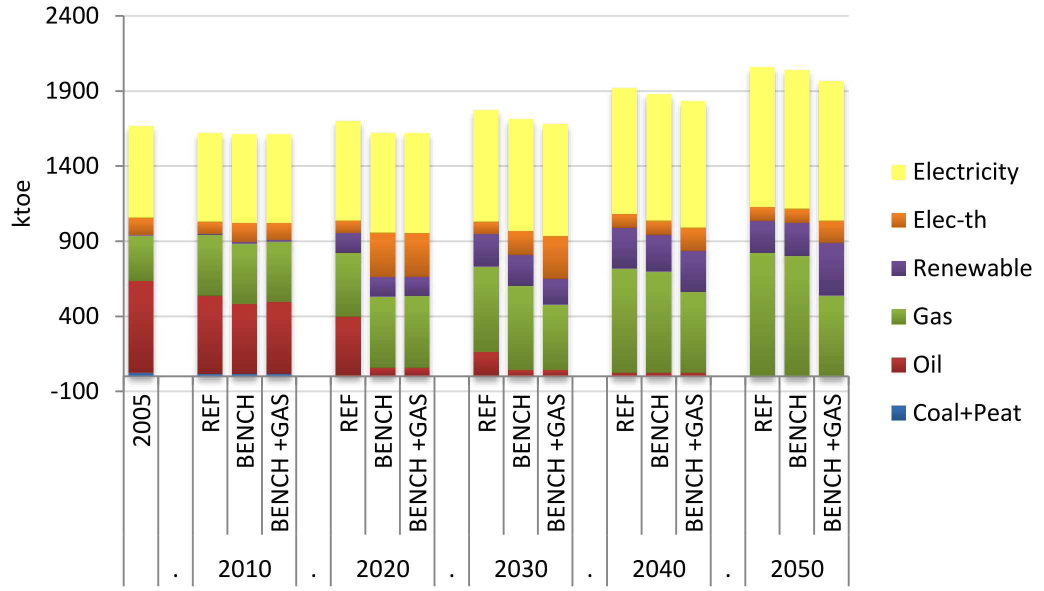

Figure 3.22 Services Sector Total Final Energy Consumption

3.3.4.4 *INDUSTRY SECTOR*

The industry sector similarly transitions through a gas dominated mix in the medium term, while temporarily substituting electrical process over the decade to 2030. By 2050, significant substitution to biomass wood products and marginal use of industrial waste account for the renewable energy substitution for gas.

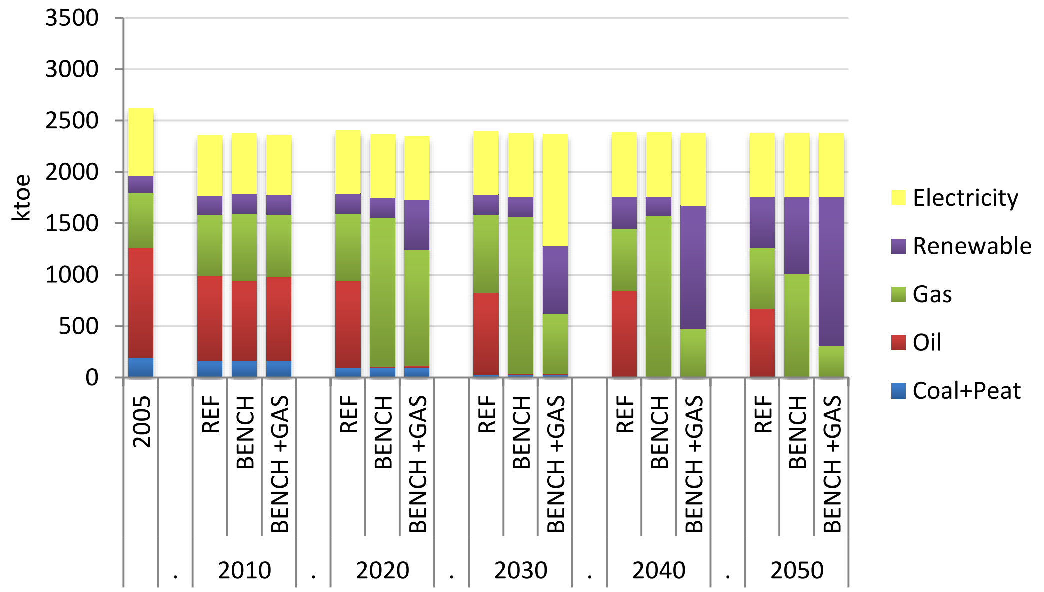

Figure 3.23 Industry Sector Total Final Energy Consumption

3.3.4.5 ELECTRICITY GENERATION

Coal consumption accelerates relatively earlier post 2020 to dominate electricity generation by 2030. This trend continues where gas in almost squeezed from the electricity generation mix by 2050, and the remaining energy required is made up by wind and hydro at 23% of gross electricity consumption.

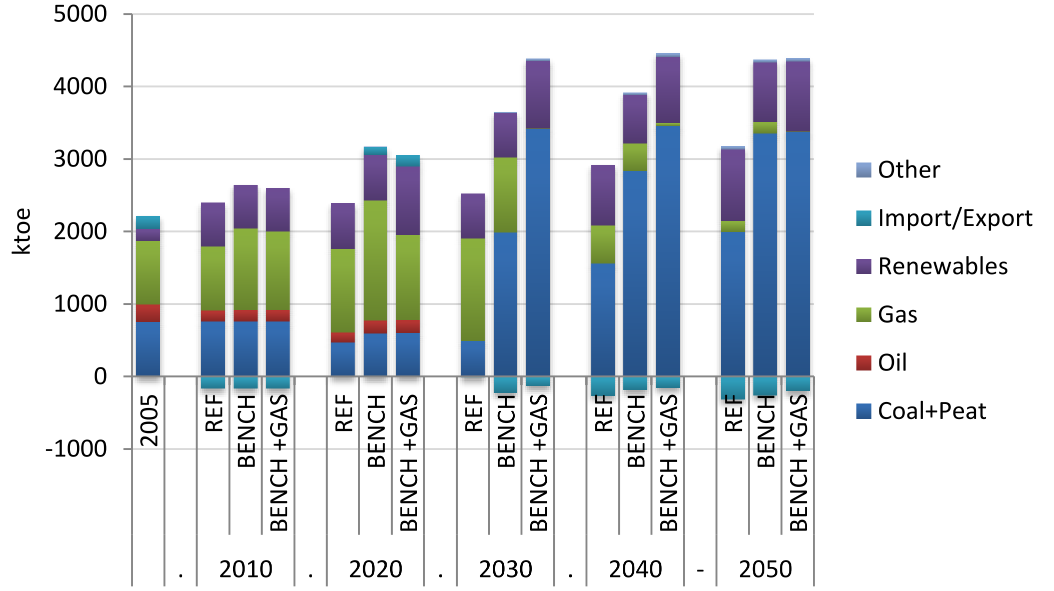

Figure 3.24 Electricity generation by primary fuel source

	REF	REF	Cost_Bench	Cost_Peak	Cost_Bench +Gas	REF	Cost_Bench	Cost_Peak	Cost_Bench +Gas
Percentage TFC	2005	2020				2050			
Coal	6.2%	3.1%	3.0%	3.1%	3.1%	0.0%	0.0%	0.0%	0.0%
Oil	62.2%	56.7%	10.7%	7.4%	10.9%	37.8%	2.5%	0.5%	3.0%
Gas	12.2%	15.7%	54.0%	57.3%	52.0%	30.5%	45.5%	53.9%	17.1%
Electricity	14.7%	14.4%	14.4%	13.9%	14.4%	15.5%	20.6%	16.8%	24.9%
Elec-Th	2.9%	3.8%	9.7%	10.2%	8.9%	3.0%	8.3%	7.5%	7.9%
Renewables	1.6%	6.4%	8.1%	8.2%	10.7%	13.2%	23.1%	21.3%	47.1%
Annual growth from 2010 ref		2020				2050			
Coal		-4.9%	-4.9%	-4.9%	-4.9%	-29.8%	-29.8%	-100.0%	-29.8%
Oil		0.3%	-15.1%	-18.3%	-15.0%	-0.6%	-7.3%	-10.7%	-7.2%
Gas		0.6%	13.9%	14.5%	13.4%	2.2%	3.0%	3.6%	0.2%
Electricity		0.7%	0.8%	0.3%	0.6%	0.7%	1.2%	0.9%	1.4%
Elec-Th		0.5%	10.4%	10.9%	9.4%	-0.1%	2.2%	2.2%	1.8%

Renewables		9.3%	12.0%	12.0%	15.0%	4.5%	5.7%	5.7%	7.3%
Services TFC		2020				2050			
Renewables	0.2%	7.9%	8.0%	8.0%	8.0%	10.5%	10.8%	11.1%	18.0%
Coal	1.5%	0.3%	0.4%	0.4%	0.4%	0.0%	0.0%	0.0%	0.0%
Electricity	36.6%	39.0%	40.9%	41.1%	40.9%	45.2%	45.4%	45.2%	47.2%
Elec-th	6.9%	4.8%	18.3%	17.9%	18.0%	4.3%	4.5%	4.5%	7.4%
Gas	18.1%	24.8%	29.1%	29.2%	29.3%	39.7%	39.0%	38.9%	27.1%
Oil	36.6%	23.2%	3.4%	3.4%	3.4%	0.3%	0.3%	0.3%	0.3%
Industry TFC		2020				2050			
Renewables	6.2%	8.0%	8.1%	8.1%	20.8%	20.9%	31.4%	32.0%	60.8%
Coal	7.4%	4.1%	4.1%	4.1%	4.1%	0.0%	0.0%	0.0%	0.0%
Electricity	25.1%	25.5%	26.0%	26.0%	26.2%	26.2%	26.2%	26.2%	26.2%
Gas	20.7%	27.5%	61.4%	61.4%	48.0%	24.8%	42.2%	41.7%	12.8%
Oil	40.7%	34.9%	0.5%	0.3%	0.9%	28.1%	0.2%	0.2%	0.2%
Residential TFC		2020				2050			
Renewables	0.9%	9.6%	11.5%	11.7%	11.9%	21.5%	22.2%	22.4%	23.7%
Coal	17.6%	8.9%	9.4%	9.6%	9.7%	0.0%	0.0%	0.0%	0.0%
Electricity	13.9%	13.7%	14.4%	14.7%	14.9%	14.1%	14.4%	14.5%	15.4%
Elec-th	7.9%	12.7%	30.9%	33.8%	28.5%	10.7%	32.2%	31.8%	27.3%
Gas	20.4%	27.4%	28.9%	29.5%	29.8%	30.5%	31.2%	31.4%	33.5%
Oil	39.4%	27.8%	5.1%	0.8%	5.2%	23.3%	0.0%	0.0%	0.0%
Transport TFC		2020				2050			
Renewables	0.0%	3.4%	6.9%	6.9%	7.0%	7.3%	26.1%	21.6%	74.6%
Electricity	0.1%	0.2%	0.3%	0.3%	0.3%	1.0%	10.8%	5.9%	19.1%
Gas	0.0%	0.2%	76.8%	76.8%	76.6%	31.1%	61.4%	71.5%	3.8%
Oil	99.9%	96.2%	16.1%	16.1%	35.1%	60.6%	1.7%	1.0%	32.6%
Sectoral Percentage of TFC		2020				2050			
Agriculture	2.8%	3.0%	3.0%	3.0%	3.0%	3.1%	3.3%	3.1%	3.7%
Commercial	14.1%	13.8%	13.1%	13.1%	13.2%	14.7%	15.8%	14.6%	17.0%
Industry	22.2%	19.5%	19.1%	19.2%	19.1%	16.9%	18.4%	17.0%	20.6%
Residential	24.9%	24.8%	23.5%	23.2%	23.0%	22.1%	23.5%	21.6%	24.5%
Transport	35.9%	38.8%	41.3%	41.5%	41.7%	43.2%	39.1%	43.7%	34.2%

Table 3.2 Scenario result summary statistics

3.3.5 System costs

The model scenarios annualised total system cost, the total required annual investment, and the subdivisions of required capital investment for transport and residential sectors are outlined in Figure 3.25. Given the radical nature and magnitude of the infrastructural change, considerable costs are incurred. The total annual system cost for the bench and peak scenarios for 2020 are up 18% and 36% respectively in comparison to the reference scenario of the same period of €13.3

billion. As mentioned previously, this cost includes investment costs, fuel costs, activity costs, operation and maintenance costs, and less terminal values of plant.

System costs for the bench +gas scenario are of comparable scale to the bench and peak scenarios; while the oil activity cost is less than that of the peak scenario, the gas import costs are more expensive than the benchmark scenario gas import costs. Furthermore, this reduced availability of fuel substitutability in the bench +gas scenario is seen also in higher investment costs in the transport sector even in comparison to the very high oil price, peak scenario. Thus the model requires further penetration of renewable energy technologies, earlier, at relatively higher cost.

3.3.5.1 Investment Costs

Significant investments in new technologies are required to attain a least cost solution, enabling fuel substitution away from oil powered technologies. Annual investments (given perfect foresight) are up 12.7% and 17.3% in 2010 from reference for both bench and peak scenarios. Investment growth rates to 2020 are 10.3% and 10.7% respectively, slowing over the model horizon to an average 3.3% growth for both model scenarios to 2050.

Investment in the transport sector accounts for the lion's share of annual investment, accounting for 68% and 66% of investment respectively in 2020 to 77% & 74% for bench and peak scenarios in 2050. On average annual transport investment is up 7.6% over the model horizon in comparison to the reference case. In 2020 investment for the transport sector is estimated at €5.6bn up 8.1% from the reference scenario for both the bench +gas and peak scenarios with a focus on small gas cars and gas fuelled heavy duty trucks in the haulage industry. 2050 sees a further increase of required investment of 14.8% and 6.9% for the bench +gas and peak scenarios over and above what the least cost reference scenario requires, with new investment in plugin hybrid vehicles with continued transition of the freight vehicle stock to gas with biodiesel trucks receiving strong investment in the Bench +Gas scenario.

Similarly, the residential sector investment on average over the horizon is up 13% in comparison the reference scenario. However, the residential sector requires a smaller proportion of all investment accounting for 12.3% of total investment in 2020 and 7.9% investment in 2050.

The services and industrial sectors require comparably much lower levels of capital investment. Where investment does occur it is in transition of thermal processes towards new high efficiency gas boilers of appropriate plant capacity in both the Bench and Peak scenarios. Investment costs of approximately €160M p.a. over the period of 2020 to 2050 are observed for the Bench and Peak scenarios for the services sector, where industry total annual capital investments of €100M are typical over the same period. The Bench +Gas Scenario incurs additional 30% investment in commercial and industry sectors seen as greater investment in wood chip and biomass boilers occurs to ameliorate increased gas costs.

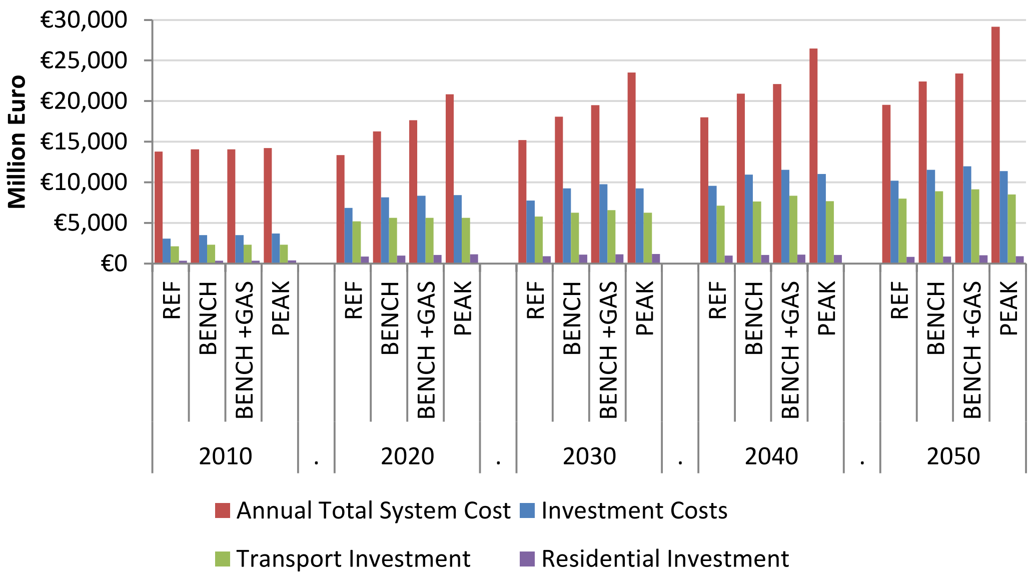

Figure 3.25 Annual total system costs, total investment costs, transport investment costs and residential investment costs

3.3.5.2 *Investment Affordability*

The affordability of the energy system and the required investments are summarised in the subsequent

Figure 3.26. The affordability of the system varies significantly across the model horizon and between scenarios. Total system cost in 2020 accounts for 8.7% GDP for the reference case up to 13.7% of GDP for the peak scenario. Given the projected GDP growth to average 1.8% p.a. over the period to 2020, the larger annual 2% and 4.9% cost differential of GDP between the reference, bench and peak scenarios is a significant challenge to economic growth. The three price scenarios require an approximate increase of 2% in investment relative to the reference case up to 2020, declining to 0.5% out to 2050. In the short term the peak scenario costs more than bench+ gas scenario, while the reverse is true in the long term beyond 2020. Transport and residential sectors maintain their proportional share of investment growth required to meet their energy service demands.

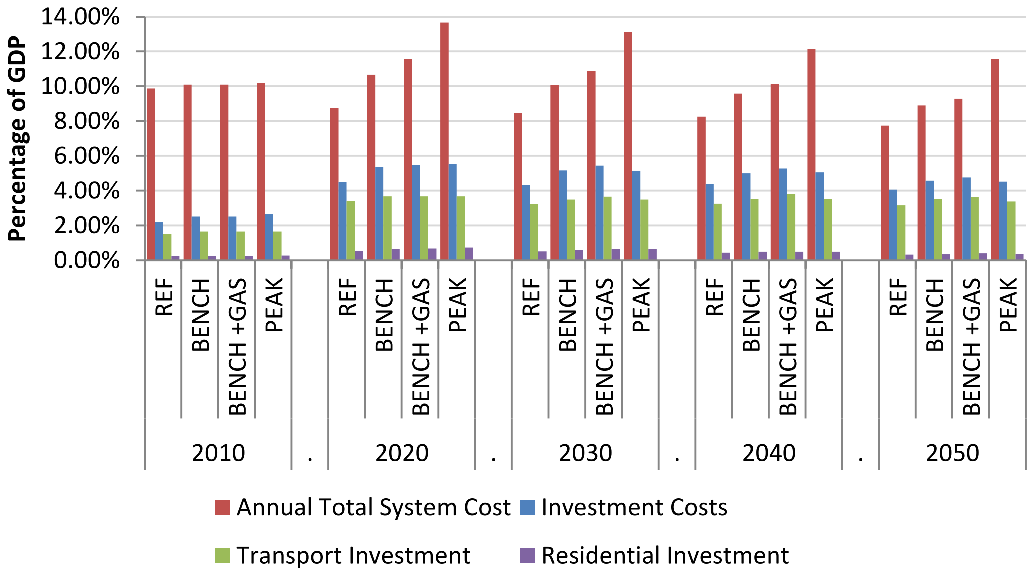

Figure 3.26 Annual total system costs, total investment costs, transport investment costs and residential investment costs as a percentage of GDP

3.4 Discussion

The volumetrically constrained scenarios (Vol +0.8% and Vol -2%) are interesting from a hypothetical point of view to show the consequences of a rationing protocol where commodity prices are maintained, but oil import reductions are imposed to prevent or reduce the effect of price shocks. The comparatively larger reduction in oil consumption as a result of the price signal indicates Irish price sensitivity to imported oil consumption relative to an average international substitutability and dependence. It is seen that current domestic oil consumption is declining faster than either the bench or peak scenarios primarily as a result of oil demand destruction, reduced energy intensity, and a shift in the structure of the Irish economy given the current economic crisis.

In the medium term to 2020, the model price constrained scenario results concurrently point to considerable level of substitution to natural gas for transport, residential, services, and industry sectors for motive and thermal processes with secondary electrification. This results in gas becoming the dominant fuel source for Ireland, at approximately 54% total final energy consumption in 2020, supplanting oil from reference projections of 57% to 10.8% TFC in 2020. Gross gas requirements more than double from a reference of 4098 ktoe to 9884 ktoe and 8610 ktoe for the bench and bench +gas scenarios in 2020. 509 ktoe of this gas is produced domestically, with the vast majority required to be imported via UK interconnectors or alternative LNG trade.

This substitution is most radical in the transport sector where the 99% TFC dominance of oil currently would be near completely removed by 2020 of the domestic transport vehicle stock (See Figure 3.27). This would require a complete new car stock and associated infrastructure, with similar upgrades to the freight and passenger transport fleet. The transport sector exhibits minimal rates of electrification and development of biofuels are limited by resource constraints; as such the least constrained technology choice is to increase levels of natural gas in the car and freight vehicle stock. Kerosene for jet aviation becomes the primary consumer of oil fuels by 2020. Domestic and International aviation suffer increased cost through the lack of fuel substitutability away from jet fuel grade kerosene.

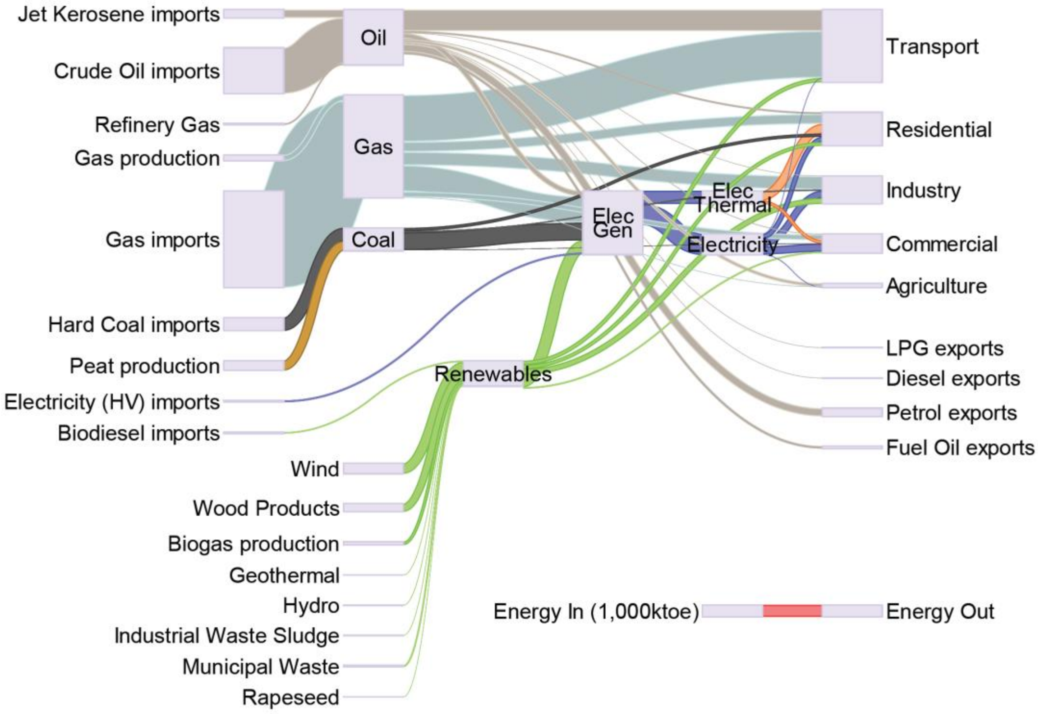

Figure 3.27 Irish TIMES Benchmark +Gas Costs Scenario Energy System for 2020

In the long-term beyond 2020, the roll of cheap coal in the electricity generation mix reducing efficiency and the shifting dominance of gas or biofuels in the transport and industry sectors are the largest contention. The deciding factors in these developments will be the outcome of climate change policy, carbon taxes explored in (Chiodi et al., 2013b; Ó Gallachóir et al., 2013), and developments in price gradient between oil, coal and gas explored in this paper. See Figure 3.28 and Figure 3.29 for this comparison. These price gradients could evolve as a result of supplies of US unconventional gas exports into European gas markets, a nascent unconventional gas industry in Europe, and/or EU natural gas pricing mechanism that are no longer indexed to oil.

The significant point to note here is that, the results from the scenario analysis indicate that the case of extremely high oil prices (Peak) is more affordable given an affordable substitution option into natural gas technologies with low natural gas prices. However, the Bench+Gas scenario with high IMF benchmark oil prices and indexed gas prices would cause significant difficulties for economic growth and resultantly affordability of optimum substitution technology choices.

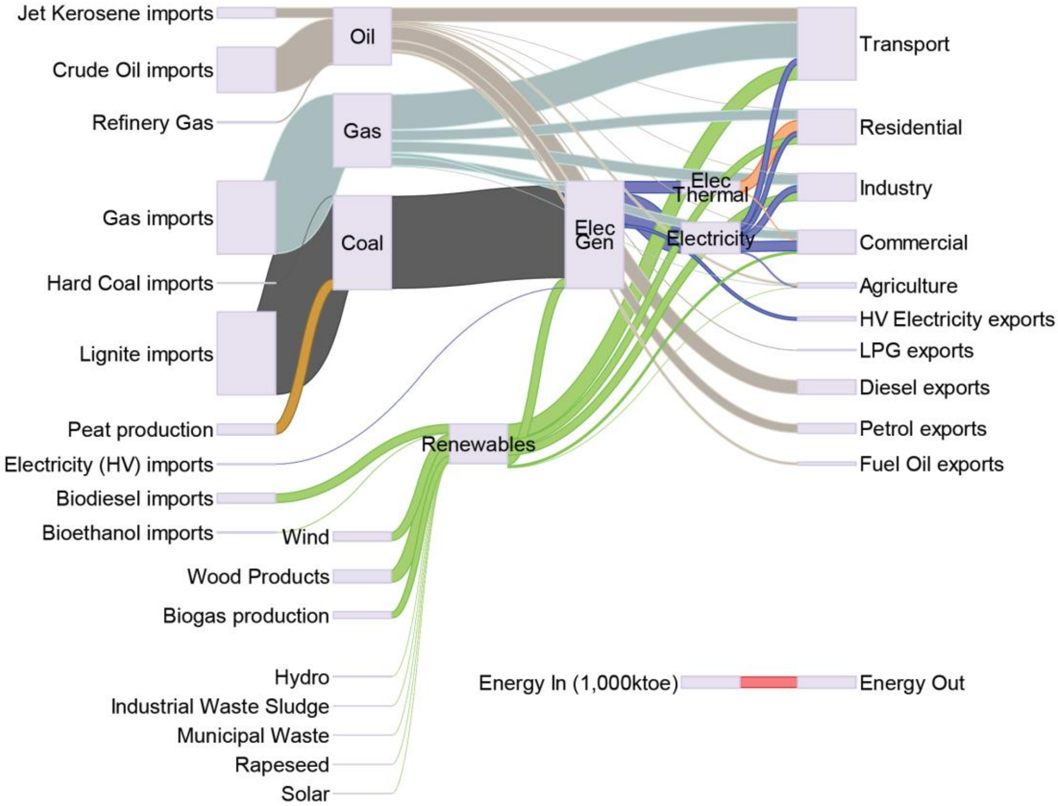

Figure 3.28 Irish TIMES Benchmark Costs (IMF1) Scenario Energy System for 2050

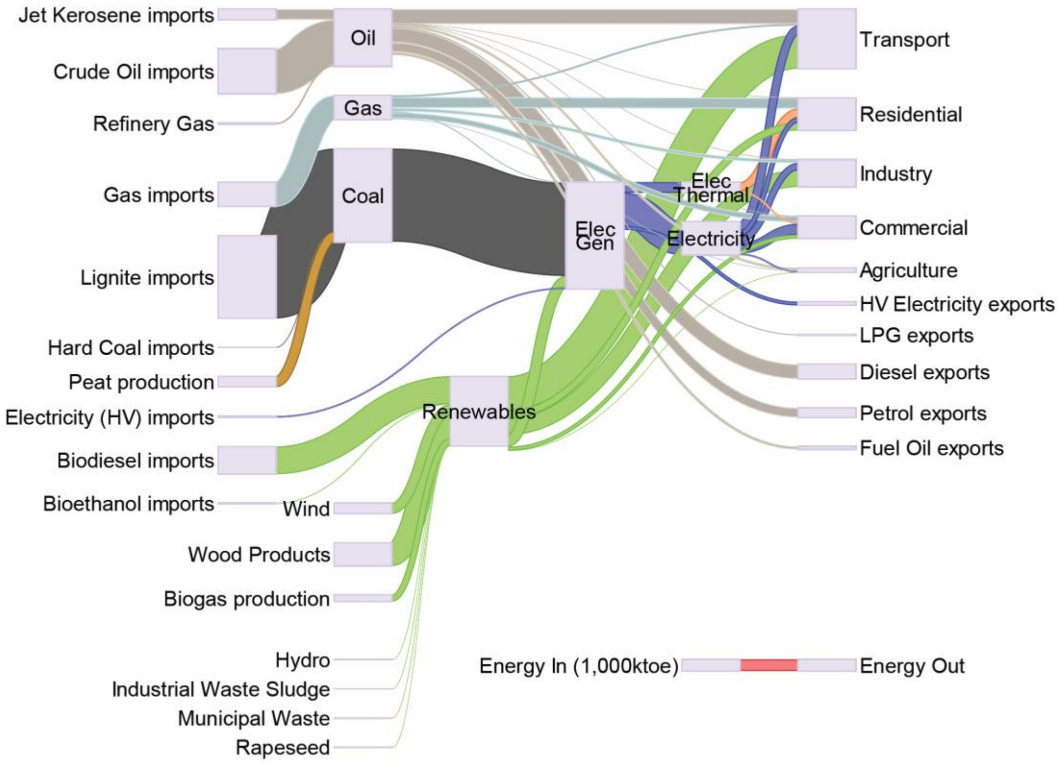

Figure 3.29 Irish TIMES Benchmark +Gas Costs Scenario Energy System for 2050

These scenarios have inherent uncertainty given the pricing assumptions. It should be highlighted that these scenarios rely heavily upon gas substitution. While some respite indigenous production in the Corrib field is expected online by 2015, pipeline interconnectors which join to a single terminal in Moffatt Scotland, with multiple connections to the spine of the UK gas grid, are at 94% peak utilisation capacity (gaslink, 2012). This capacity is dependent on the Beattock pumping station pressure. The station has equivalent to a theoretical energy capacity of 342GWh/d (29.4ktoe/d) (Macevilly, 2013), but network reinforcements & storage would be required. Moffat terminal capacity utilisation is projected to be at 108% capacity by 2015 without Corrib. While the scenario solutions are least cost, a current over reliance upon oil supplied through multiple ports in Ireland, becomes a larger reliance on a single supply route of natural gas. We may or may not be entering a global golden age of gas (International Energy Agency, 2011b), however it would be prudent to assess the cost and risk of reduction of fuel diversity and supply diversity.

Social optimum scenarios which account for the dual problems of climate change and energy security need to concurrently account for GHG reduction targets and the value of energy security policies are required to be simulated.

The collapse of the construction bubble commenced a free fall of road freight energy consumption (-49%) over the years 2007-2011, and started the restructuring of the Irish economy away from heavy energy demand construction towards lower energy demand per unit value added services such as IT and software development. This in turn may leave road freight at diminished levels of energy demand, however, being an island economy Ireland remains open and dependant on other oil fuelled freight transport. Elastic demand or modal shifting in the transport sector is not modelled in this analysis.

The issues of feedback between energy prices and energy service demand to the macroeconomic driving assumptions are not addressed in this work. While high oil prices are known to have a dampening effect on personal consumption and economic growth (Kelly and Clinch, 2010), this work assumes the long term economic outlook remains consistent across all scenarios.

Therefore, the differences in scenarios should not be taken as forecasts in their own right, but should be assessed in the relative differences between scenarios to assess potential for risk mitigation, appropriate infrastructural investment and government policy that they require. Indeed the infrastructure costs required to enable the energy technology changes envisaged in some of these scenarios warrant further investigation.

Lastly, while this analysis focuses on Ireland, elements of the analysis are universally true. Technology choices are driven by price gradients of the commodities consumed. Figure 3.4 shows the divergent trends both between the US and Europe and by energy commodity for price per unit of energy. Cheap US Shale gas is already causing a change in the merit order in the US electricity generation sector, prioritising gas over coal in 2012. Similarly given the price gradient between US oil and US gas, the supply glut and difficulty in establishing LNG export capability, investment in natural gas vehicles where supply infrastructure meets potential demand would make economic sense. A similar case can be made for continental Europe's transport fleet with costs much closer to Ireland, with higher population densities and more interconnected gas grids. The current trend in Europe and the Irish scenarios results in this analysis of growing coal fired power generation is a worrying trend if greenhouse gases (GHG) are to be appropriately mitigated.

3.5 Conclusion

The aim of this section is to explore energy security scenarios for Ireland. This goal has resulted in focus on the immediate dependence upon oil and the vulnerability of the energy system to oil supply shortages and sustained price shocks. The analyses methodological approach combines Irish TIMES, the Irish energy systems model, with the International Monetary Fund's research department's oil price & supply scenario projections for constrained global oil supply. These projections are based on the IMF's in house global dynamic stochastic general equilibrium model (GIMF) for scenarios of increasing price volatility and supply contraction. This work focuses upon the Irish calibrated reference energy system, combined with the IMF benchmark and downside ("peak") scenarios, disaggregated into two oil import volume constrained scenarios, and three detailed price constrained scenarios.

In 2003, the cost of net oil imports to Ireland stood at €1.46 billion (1.0% GDP). In 2012 the cost of net oil imports stands at €3.6 billion (2.26% GDP) (Central Statistics Office of Ireland, 2013). The Eurozone debt crisis has had a detrimental effect on the value of the euro and the subsequent ability to trade and import commodities denominated in US dollars. The annual average Brent oil price for 2011 and 2012 respectively is €79.9/bl and €87.1/bl; a 9% increase year on year and a 34% increase since the dollar spot price maximum in 2008.

In the possible scenario where global oil supply remains in its current stagnated state with minimal supply growth, the “bench” scenario energy system pathway outlines a least cost energy system for an additional annual cost of €2.9 billion by 2020 or 1.9% of GDP, in comparison to the reference case. The worse-case, in which global oil supply begins to contract at 2% p.a. and the subsequent price increases instigate a process of rapid fuel substitution and demand destruction shows a least cost energy system for an additional annual cost of €7.5 billion by 2020 or an additional 4.9% of GDP. An annual cost of this magnitude could potentially undermine the ability of the economy to grow, however this being the least cost solution for this scenario, continuing the current energy mix consumption trend would be more costly.

In the case where gas prices remain indexed to oil prices, and global oil production remains stagnant, gas is used as a transition fuel to 2020. This is a useful outcome, that both costs-bench and bench +gas scenarios show similar energy systems to 2020. Beyond 2020, a greater divergence occurs where renewables penetration increases, where most noticeably biofuel imports substitutes for natural gas imports in the transport and industry sectors.

ACKNOWLEDGEMENTS

Supported by the Higher Education Authority of Ireland through the PRTLI-5 Graduate Research Engineering Programme in Energy

The authors acknowledge funding provided by the Environmental Protection Agency and Sustainable Energy Authority of Ireland under Ireland's Climate Change Research Programme 2007 – 2013 for the development of the Irish TIMES model. (2011 – CCRP – MS - 3.5)

The authors acknowledge research from the International Monetary Fund (IMF) in their World Economic Outlook (2011) on Oil Scarcity, Growth and Global imbalances, which forms a partial basis for this work, and training in their global integrated monetary and fiscal model (GIMF).

Chapter 4 Economic Impacts of Future Changes in the Energy System – Global Perspectives

Primary Output:

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4.1 INTRODUCTION

4.1.1 *WHY LINK ENERGY-ECONOMY MODELS?*

In this two part chapter the current state of the art of methods within the ETSAP community to couple energy systems models to macroeconomic models are presented. Part one covers perspectives on the environmental rationale, model coupling development, and outlines model coupling policy and research applications at the global and regional level. Part two continues with national case studies, showing the UK's legislative use of the coupled hybrid MARKAL[6]-MACRO (MM) model, and updates to the mathematical formulations of its successors TIMES[7]-MACRO (TM) and most recently TIMES MACRO-Stand-Alone (TMSA). The energy systems models discussed are bottom-up (BU) techno-economic linear optimisation engineering TIMES models, and are coupled to top-down (TD) macroeconomic models. These range from single producer-consumer agent production function models, to multi-region structural computable general equilibrium (CGE) models. Both parts of the chapter collate the collective work that was presented at an IEA-ETSAP funded workshop in University College Cork in February 2014.

The chapter concludes by synthesising common critical messages from the range of studies. The applied theory of what constitutes a consistent, pragmatic and heuristic model linkage is discussed. Soft-linking and hard-linking multi-model methods are introduced with attention paid to model structures, consequent data harmonisation and data transfer frameworks. Multi-regional models add insight into trade and competition effects upon delocalisation. Overall, maintaining a consistent paradigm throughout model coupling is critical in understanding the economic impacts of future changes to the energy system.

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[6] MARKAL – **MARK**et **AL**location model
[7] TIMES – **T**he **I**ntegrated **M**ARKAL-**E**fom **S**ystem

Affordable access to an acceptable energy supply is critical for a prosperous stable economy. Functional markets are theorised to price primary energy supply commodities, their refined products and final consumer energy products. Non market externalities such as green-house-gas (GHG) emissions or long term strategic policy decisions are difficult to fully include in near term commodity futures pricing, as a result of changing trends and resultant uncertainty. Half of all cumulative anthropogenic CO_2 emissions have occurred in the past 40 years. Increasing energy system carbon intensity between 2000-2010 has contributed to GHG growth increasing to 2.2%/year when compared with 1.3%/year over the previous three decades (IPCC, 2014). Two thirds of global GHG emissions are produced by the energy system. The energy system analysis of International Energy Agency's (IEA) New Policy Scenario leaves the world on track for a long term average temperature increase of 3.6°C, dangerously beyond the 2°C limit (IPCC, 2013; OECD/IEA, 2013). A restructured low-carbon world economy is thus imperative (Capros et al., 2014; Krey et al., 2014).

Internalising the energy system GHG environmental externality by appropriate pricing mechanisms via emissions permits trading markets and carbon taxation is seen as the primary means to drive decarbonisation in the energy system. In energy systems modelling, the marginal abatement cost of carbon is typically used as the scenario comparison yard-stick. Carbon pricing is critical to stabilise investor expectation and to promote investment in marginal mitigation technologies. The European emissions trading scheme (EU-ETS) has made efforts to account for the environmental externality, but thus far has failed to be the causal force in reducing carbon emissions. It must be fixed, and other regions must similarly collaborate (Edenhofer, 2014). Otherwise, climate change - essentially a commons problem - could become the modern era "tragedy of the commons" (Hardin, 1968; Nordhaus, 1994). Recently the UK has made efforts to correct this market failure with amending policy to introduce a carbon price floor (HM Revenue & Customs, 2013). Revenue recycling schemes from carbon taxation can bring long term decarbonisation benefits to near term social good, tackling climate inequality, or achieve revenue neutrality. Policy-makers need tools to understand the effectiveness and the economic impact of policies whose purpose is to shift energy systems toward more environmentally desirable development pathways (Hourcade and Jaccard, 2006). Understanding energy-economy coupling is crucial in analysing regional effects of carbon tax, trade, competitiveness, and energy policy at large.

Accounting the cost of investment required to achieve least cost energy systems is achievable with technology rich BU energy systems models. The rationale behind linking engineering energy systems models with macroeconomic models is to include the feedback effect between energy cost and energy service demands. Coupling energy-economy models enables analysis of heterogeneous sectoral dynamics while providing a more suitable microeconomic framework (Bataille et al., 2006), that energy systems models on their own can only approximate with elastic demand. The objective is to estimate the changes in welfare and growth, where deviation from business-as-usual (BAU) in investment requirements induces productivity and consumption pattern changes through substitution effects. The potential magnitude of these effects vary considerably across differing economic schools of thought - from neoclassical to ecological economics and from growth opportunities to deep sustainability (Ayres et al., 2013; Jackson, 2009; Krey et al., 2014; Strachan and Kannan, 2008; The Global Commission on the Economy and Climate, 2014; Warr and Ayres, 2006). GHG emissions are typically the constraint driving redistribution of investment capital causing macroeconomic feedback, but of course this is not the only model scenario that could be considered. The macroeconomic cost of energy supply insecurity is an alternate use of model coupling, as is energy export and trade dynamics. The benefit of soft-linking energy system and macroeconomic models is in utilising the complementary strengths of both models to overcome the other's weaknesses. This allows additional insights of technological and economic detail to be gleaned that otherwise would not be quantified.

4.1.2 BU and TD Models

BU engineering models and TD macroeconomic models have evolved as the economically consistent means of assessing long term energy system dynamics and costs (Hourcade and Jaccard, 2006; Wene, 1996). BU models include *optimisation, simulation, accounting and multi agent techniques* (Fleiter et al., 2011). Some TD methods include *input-output, econometric, computable general equilibrium* (CGE) and *system dynamic models*. This chapter is primary focused on coupling TIMES optimisation and CGE models.

BU model methods are explicit in their data richness and outline detailed technology development pathways, interdependencies and costs. TIMES and its forebear MARKAL form the primary constituent parts of a family of linear programming models supported by ETSAP under an implementing agreement of the IEA. TIMES is a techno-economic model generator for local, national or multi-regional energy systems, which provides a technology rich basis for estimating energy dynamics over a long-term (20-50 years), multi-period time horizon. TIMES computes a time varying inter-temporal partial equilibrium on inter-regional markets. The objective function maximises total surplus. This is equivalent to minimising the discounted total energy system cost while respecting environmental, technical and scenario constraints. This system cost includes investment, operation and maintenance and fuel import costs, less export income, terminal technology values and salvage values. This approach does not consider the same microeconomic theoretical underpinnings as a TD model and can be viewed as the optimisation by a clairvoyant energy planner with perfect information and perfect foresight over the total system, rather than maximising consumer choice preferences at a microeconomic level. Thus, TIMES models reference scenario pathways are driven by energy service demands exogenously defined by macroeconomic conditions and resource supply curves, while subsequent dynamics are driven by environmental constraints under user consideration. The technical foundations of MARKAL is outlined by Fishbone and Abilock, while the full technical TIMES documentation is hosted online by ETSAP (Fishbone and Abilock, 1981; Loulou et al., 2005).

TD CGE methods describe the whole economy, mapping and subdividing sectoral structures where substitution between factors of production is allowed. CGE models are built upon microeconomic theory to calculate prices and activities in all sectors of an economy to reach a general equilibrium. Consumers maximise their utility through demanding goods met by producers who maximise profits (Arrow and Debreu, 1954; Johansen, 1960). Historical national or global accounts data is required for calibration, where the Global Trade Analysis Project (GTAP) database is the most commonly used example. TD models in general, namely CGE models, do not include many technical aspects of the energy system. The energy system combined with the other factors of production, forms of capital and labour, are described in inter-related production functions to optimise consumer utility and economic growth. Capital value shares, elasticities of substitution, and autonomous energy efficiency improvement coefficients - estimating technological learning - and marginal technology cost curves (Kiuila and Rutherford, 2013) enable estimation of technology choice and fuel switching dynamics.

The Lucas critique argues econometric models based on historic trends cannot model policy changes nor remain valid in future technology paradigm shifts (Grubb et al., 2002; Lucas Jr, 1976). CGE models usually have smooth rates substitution, whereas poorly constructed optimisation models can display a "flip-flop" binary characteristic related to the capacity size of the marginal technology choices and level of model constraints (Grubler et al., 1999). The different approaches can provide differing solutions and result in differing policy conclusions. However, CGE models can give long term macroeconomic outlooks to drive TIMES energy systems models which can in-turn feed back energy costs adjustments to the CGE model, which upon iteration provides new energy demands (Hoffman and Jorgenson, 1977). In a consistent framework the coupled hybrid model can build a more accurate representation of the system under scrutiny.

4.1.3 Hybrid model evolution

The linking of the Brookhaven Energy System Optimisation model (BESOM) with a CGE model is the first hybrid energy-economy model reported (Hoffman and Jorgenson, 1977). The outputs of each of the individual models were transferred between each other manually by the user, in what has become known in the proceeding decades as *soft-linking*. Soft-linking is typically the simplest starting point by its transparency, flexibility, learning (Martinsen, 2011), and practicality in establishing consistent common measuring points (CMP) in the overlap of model structures.

The alternative of the programmatic linking of models to automate data transfer between models is known as *hard-linking.* MARKAL-MACRO is the first such reported hard-linked energy-economy model (Manne and Wene, 1992), and is the basis for the subsequent TIMES-MACRO, TIMES-MSA and others (Manne et al., 1995; Messner and Schrattenholzer, 2000; Wene, 1996). Hard-linked models tend to establish optimum data transfer methods, enabling greater productivity, control, convergence and solution uniqueness. Historically hard-linking has come at a computational cost, requiring the model to be a reduced form single sector model (Böhringer, 1998; Bosetti et al., 2006; Manne et al., 1995; Manne and Wene, 1992; Messner and Schrattenholzer, 2000; Strachan and Kannan, 2008). This results in aggregated energy economy interactions, giving overall trends but limits its usefulness when applied to sector specific enquiries.

Combining BU and TD models in a mixed complementarity problem introduces a limited set of technological sectoral detail into a CGE framework (Frei et al., 2003; Proença and St. Aubyn, 2013; Sue Wing, 2008). The whole energy system cost optimisation problem could be integrated into a CGE model, with decomposition to improve solution algorithm performance and reduce computation time (Böhringer, 1998; Böhringer and Rutherford, 2009, 2008). However, the authors are not aware of such a model. Aside, the International Monetary Fund has made attempts to integrate oil supply dynamics into its global dynamic stochastic general equilibrium model GIMF (Benes et al., 2012; Kumhof and Muir, 2014).

4.2 Linkage of the global energy models TIAM-WORLD & GEMINI-E3

In order to assess climate mitigation agreements, an iterative procedure linking TIAM-WORLD and GEMINI-E3 is the first method proposed. TIAM-WORLD (TIMES Integrated Assessment Model) is a BU global multi-regional technology-rich optimisation model. GEMINI-E3 is a TD global multi-regional general equilibrium model (Bernard and Vielle, 2008; Loulou and Labriet, 2008). Recent work soft-linking the two models explores global and partial climate agreements (Labriet et al., In Review). An accurate representation of the energy and technology choices, and the macro-economic impacts, especially in terms of trade effects of climate polices, is critical in understanding future pathways to a climate constrained world.

TIAM-WORLD is part of the TIMES family of energy models and calculates a dynamic inter-temporal partial equilibrium on worldwide energy and emissions markets based on maximisation of total surplus (Loulou, 2008; Loulou and Labriet 2008). The version of the model uses in this application divides the world in 15 regions, driven by 42 energy service demands across all sectors. It covers the procurement, transformation, trade and end use of all energy forms, represented by over 1500 energy technologies and one hundred commodities in each region. Energy demands are calibrated by the user for the reference scenario, and each has its own price elasticity. Environmental emissions are endogenously modelled at the technology level. TIAM-WORLD integrates a climate module for the modelling of greenhouse gas concentrations, radiative forcing and temperature increase.

GEMINI-E3 is a multi-country, multi-sector, recursive computable general equilibrium model. It represents the world economy in 28 regions and 18 sectors. The standard model is based on the assumption of total flexibility on both macroeconomic markets, such as the capital and the exchange markets (the associated price are the real rate of interest and the real exchange rate, which are then endogenous), and microeconomic or sector markets (goods, factors of production). GEMINI-E3 is calibrated with the GTAP database which includes physical energy market data, social accounting matrices and bilateral trade flows.

4.2.1.1 Data Harmonisation

The initial harmonisation of the two very different model structures represents a critical challenge for theoretical consistency of the hybrid model. Each of the model regions and commodities need to be paired. Furthermore, reference scenarios require harmonisation of the basic drivers of the energy system, being population growth, GDP trends, energy prices and energy policy constraints. Once harmonized, the reference cases of TIAM-WORLD and GEMINI-E3 propose similar CO_2 emission trajectory until 2030. Differing technological assumptions lead to longer term divergence of CO_2 trajectories. This effect has also been seen in similar modelling exercises (Kanudia et al., 2014; Krey et al., 2014; Labriet et al., 2012).

4.2.1.2 The Coupling Method

The purpose of the linkage of the models is to allow the strengths of each model (technological richness of TIAM-WORLD and macro-economic details of GEMINI-E3) to augment the overall analysis of energy and climate policies. The coupling approach optimises the data flow of common market points, from the model of relatively more accuracy, to the other model. GEMINI-E3 receives data from TIAM-WORLD on energy and CO_2 prices, technical progress on energy use, and capital consumption. TIAM-WORLD receives sector economic production data to recalculate energy service demands.

TIAM-WORLD only goes through one major modification: the removal of price elasticities of the energy service demands. This microeconomic behaviour is modelled by GEMINI-E3. GEMINI-E3 requires more numerous modifications to consistently utilise the data linkages; energy technologies that are not present in the standard version of GEMINI-E3, such as biomass, hydrogen, nuclear and other renewable energy sources are added to the model structure and the nested structure of the CES functions are rewritten; the CES functions relating to all energy consumption are replaced by Leontief function, whose coefficients representing the energy shares are computed on the basis of TIAM-WORLD results; technical progress is modified with energy efficiency improvements from TIAM-WORLD; finally, energy and carbon prices are computed by TIAM-WORLD.

The coupling procedure is carried out in a Gauss-Seidel method (Hageman and Young, 2012) which seeks a fixed point for the useful demand vector through an iterative process. TIAM-WORLD is first run with useful demands from the harmonisation phase of the two models. TIAM-WORLD passes its results to GEMINI-E3, which is re-run. This is the first iteration. New macroeconomic output and industrial value added obtained from GEMINI-E3 are used to re-estimate the energy service demands. This process is repeated until model convergence is reached, defined as the Euclidean distance between the two last demand vectors over the norm of the last demand. Convergence is typically achieved in 6 iterations for climate constrained scenarios.

4.2.2 Results

Both global and partial climate agreements are studied with the proposed coupling methodology.

The comparison of the Iron & Steel production results obtained with TIAM-WORLD in a standalone manner with elastic demand and with the coupled models illustrates one of the added values of the coupling: in a global climate agreement, while the iron-and-steel production decreases in all countries in TIAM-WORLD used in a standalone manner, several countries increase their production in the coupled models to compensate the production decrease in China and India. The combined analysis of trade, provided by GEMINI-E3, and energy dynamics, provided by TIAM-WORLD, helps to understand these decisions: India and China prefer importing Iron & Steel from some other countries rather than producing it locally with clean energy and processes because of the lack of clean production opportunities in these countries compared with the others, more particularly biomass-fired power plants opportunities with carbon capture and sequestration.

However, the differences in sectoral emissions between TIAM-WORLD used in a standalone manner and the coupled models are smaller than 5% over the model time horizon. This is an interesting result, showing that the inter-sectoral effects of climate policies have little effect on overall aggregated sectoral emissions.

In partial agreements, the coupled models help the assessment of the delocalisation of not only primary energy extraction (to Former Soviet Union and Africa), represented in TIAM-WORLD but also industrial production (to Asia), provided by GEMINI-E3. However, emission leakage remains small, mainly due to global lower oil demand.

The macroeconomic analysis from the coupled models also shows fossil fuel exporting countries, represented by the Middle East, Former Soviet Union and to a lesser degree Africa, are all extremely penalized by climate constraints. This simply occurs as a result of trade imbalances consequent to energy export revenue reductions while fossil fuel production declines.

4.2.3 Discussion

The two global energy models are coupled through an iterative exchange of data until convergence of energy demands. It builds upon the technology richness of TIAM-WORLD and the macro-economic details of GEMINI-E3. Technology changes, macroeconomic and inter-sectoral effects are assessed with the coupled models.

Although such an approach minimizes the number of structural changes of the original models compared to the full integration of models within a same optimization framework (Labriet et al. in review), a meticulous examination and understanding of both models is crucial in order to define the correspondence between energy commodities, regions, economy sectors, to build the data exchanges between both models, and to avoid any methodological inconsistencies (Böhringer and Rutherford 2009).

An added value of the proposed coupling framework at a global scale is the understanding of the energy system transition interdependences upon trade and competition effects.

4.3 Global energy policies analysed with TIAM-FR and IMACLIM-R

The hybrid linking of TIAM-FR and IMACLIM-R, while conceptually similar to linking TIAM-WORLD and GEMINI-E3 (summarised in section 4.2), is fundamentally different in a specific assumption of perfect foresight. The CGE model IMACLIM-R allows the exploration of the differences in myopic technology pathways due to recursive time dynamics, i.e., the model is solved in sequential (yearly) time steps, linked through time by capital accumulation based on exogenous savings rates, while TIAM has perfect foresight of technology availability and development. This first section focuses on the reconciliation of these theoretical differences.

TIAM-FR, a version of the TIMES Integrate Assessment Model (TIAM) developed in France, is a typical BU TIMES model that has been widely used to assess sectoral and global energy and climate policy from both developed and developing countries perspective (Assoumou and Maïzi, 2011; Bouckaert et al., 2011; Ricci and Selosse, 2013). IMACLIM-R, is the recursive version of IMACLIM, a multi-regional multi-sector TD model that has been developed by CIRED to assess the long-term global economic impacts of climate policy (Guivarch et al., 2009; HAMDI-CHERIF et al., 2011; Mathy and Guivarch, 2010; Rozenberg et al., 2010; Sassi et al., 2010)

The divergent viewpoints of models developed by energy engineers, or BU models, and those developed by economists, or TD models, can hinder effective dialogue and mutual understanding between researchers from different academic backgrounds. The purpose of this work is to promote a constructive dialogue between modellers from each side of the modelling paradigms, based on a comparative critique of the BU TIAM-FR model and the TD IMACLIM-R model.

4.3.1 Method

First and foremost, the conceptual frameworks (optimisation *vs.* recursive) of the two models must somehow be reconciled, and is done with a descriptive 3 axis approach. TIAM-FR results are ‘normative’ in the sense that they describe cost-minimising investment and consumption trajectories under perfect foresight. Conversely, the simulation results of IMACLIM-R are 'positive' economic trajectories that imbue some inefficiencies stemming from the fragmented nature of decision making and the assumption of myopic or imperfect anticipations. The bridge between these approaches can somewhat be gapped by introducing a set of constraints in TIAM-FR that could emulate some of the sub-optimal features of real economies modelled by IMACLIM-R. Typically, trade on strategic international markets as that of crude oil can be exogenously constrained, and the rents on crude oil markets represented by increased trading costs.

Another possible way of conciliating the two approaches is by simply accepting that a part of the economic system, the part regarding the supply of energy and end-use energy technologies, could be governed in a much more centralised and rational manner than the rest of economic activity. Despite the decentralised nature of energy demand decisions this case could be made considering the extent of policy intervention in energy policies, both on the supply and the demand side of markets. The core divergence remains, however, that TIAM-FR operates under perfect foresight, notwithstanding any additional constraint aimed at controlling its trajectories.

The second axis of research that must be investigated in coupling experiments is that of the modelling scopes, namely regarding renewable decentralised energy production. IMACLIM-R does not model traditional biomass, nor is it well equipped to describe other renewable power production, for the reason that the energy consumption derived from these new technologies are not backed by market transactions. From an aggregate point of view, renewable power production can be modelled as a substitution of capital to energy consumption — but this is true also of any improvement of the energy efficiency of end-use technologies, and the two effects should probably be decoupled. Turning to TIAM-FR, the availability of any economic information beyond energy markets is brought into question. Its explicit representation of end-use technologies, and most importantly building construction and retrofit and personal cars, implies that TIAM-FR reaches beyond energy demand to depict the demand for different equipment sectors.

The third axis of any coupling experiment is a comparison of nomenclature and terminology. On the supply side of energy markets, the cost structures of electricity production depicted in TIAM-FR are synthesised in one aggregate sector by IMACLIM-R. Thus, the capital intensity of the electricity sector will have to reflect the various impacts of the penetration of renewable alternatives and nuclear electricity, while it will also have to translate the anticipated infrastructure developments — the investment costs of smart-grid deployment; its gas and refined petroleum products intensities shall translate the evolution of fossil-fuel based electricity, while its intensity in agricultural products will be asked to reflect any biomass penetration.

TIAM-FR is geographically aggregated in 15 world regions. It covers the time horizon from 2005 to 2100, the year generally selected to properly reflect the long-term nature of the climate constraint. Indeed, a climate module computes the change in CO_2 concentrations in atmospheric radiative forcing from anthropogenic activities and the temperature change relative to the pre-industrial period. The climate module does not induce retroactive energy services demands, which remain unchanged. More generally, TIAM-FR is driven by 42 exogenous end-use energy demands grouped into six sectors. Each energy demand is calibrated for the base year, and then follows a trend induced by some exogenous driver, *i.e.* regional economic and demographic projections and region-specific elasticities.

IMACLIM-R provides a more aggregated view of global economic activity, which it divides into 12 regions and 12 sectors. The base year of the model (2001) builds on the GTAP-6 database, a balanced Social Accounting Matrix (SAM) of the world economy, although the original GTAP-6 dataset was modified to (i) aggregate regions and sectors according to the IMACLIM-R mapping, and (ii) accommodate the 2001 IEA energy balances (Rozenberg et al., 2010; Sassi et al., 2010).

IMACLIM-R's rationale stems from the necessity to understand better, amongst the drivers of energy-economy prospective trajectories, the relative role of (i) technical parameters, (ii) structural changes in the final demand for goods and services (dematerialisation of growth patterns) and, (iii) micro and macroeconomic behavioural parameters in open economies. This is indeed critical to capturing the mechanisms in the transformation of a given environmental alteration into an economic cost and in the widening or narrowing margins of freedom for climate mitigation or adaptation.

To fully exploit the potential of this dual representation requires abandoning the use of conventional aggregate production functions, which roughly represents the technological constraints impinging on an economy (Berndt and Wood, 1975) and (Jorgenson, 1982). It is indeed arguably impossible to find mathematical functions flexible enough to encompass all the contrasted scenarios resulting from the interplay between consumption styles, technologies and localisation patterns (Hourcade, 1993), for small as well as for large departures from the reference equilibrium. This accounts for the reported absence of formal production functions in IMACLIM-R (Sassi et al., 2010).

IMACLIM-R and TIAM-FR use the same data and scenario with regards to the growth of population, from the United Nations. The global geographical division in TIAM-FR have been reprocessed from the simulation outcome of IMACLIM-R and re-aggregated in accordance with its 15 regions. The macroeconomic indicators were integrated into the TIAM-FR model to drive the energy service demand and, from it, determine the energy system in an optimisation framework. TIAM-FR model is then re-run with the macroeconomic output indices coming from IMACLIM-R to calculate the optimal outcome of the energy supply system and carbon emissions trajectories at the world level.

Three Scenarios are considered, a business as usual scenario (BAU), and two climate scenarios (CLIM), one with BAU drivers, Clim_dBAU and the third scenario with drivers from a climate run of IMACLIM-R, Clim_dClim. More precisely, BAU scenario from TIAM-FR is based on macroeconomic indicators extracted from the BAU scenario of IMACLIM-R. Concerning the climate scenario, CLIM_dBAU and CLIM_dCLIM refer to two different trajectories consistent with the 450ppm target in 2100 for CO_2 emissions. CLIM_dBAU is derived from simulation based on the BAU growth indices in IMACLIM-R, whereas CLIM_dCLIM is driven by growth indices from the 450 ppm scenario in IMACLIM-R. The price elastic energy demand functions are not used in running TIAM-FR as the prices have not been harmonized between the two models.

4.3.2 RESULTS

The results specifics are not in focus here but more so the relative impact between scenarios are of interest in investigating the demand reduction as a result of climate scenario in IMACLIM-R. CO_2e emissions paths induced by climate constraints are reported in the Figure 4.1.

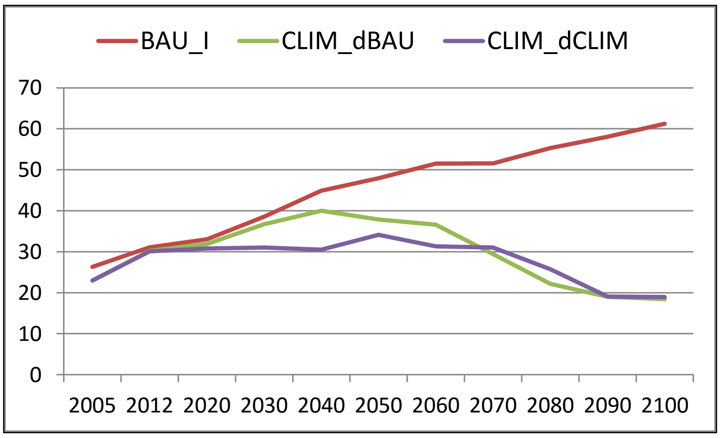


Figure 4.1 World CO_2e emission trajectories under the three example scenarios (Gt)

The comparison of CLIM_dBAU and CLIM_dCLIM pathway shapes illustrates again the divergence between TIAM-FR and IMACLIM-R in terms of modelling philosophy. Under an inter-temporal optimized abatement trajectory (CLIM-dBAU), emissions may keep growing by 2040 then slightly drop until 2060 before declining sharply. By contrast, the agent cannot see this *optimal* abatement pathway in the IMACLIM-r. Therefore, the pricing signal must be very strong, to reflect the 450 ppm constraint to curtail the fossil-fuel dependent goods and services demand. The growth indices would be much lower than in the case of the *optimal* growth in the short and mid-term. However, in the long run, there would be more flexibility for emission growth in CLIM-dCLIM than CLIM_dBAU as the economy will be largely decarbonized and thus offers more room for an emissions increase. TIAM-FR and

IMACLIM-R suggest different timing and arbitrage for sectoral emission abatement for a given climate target (See Figure 4.2).

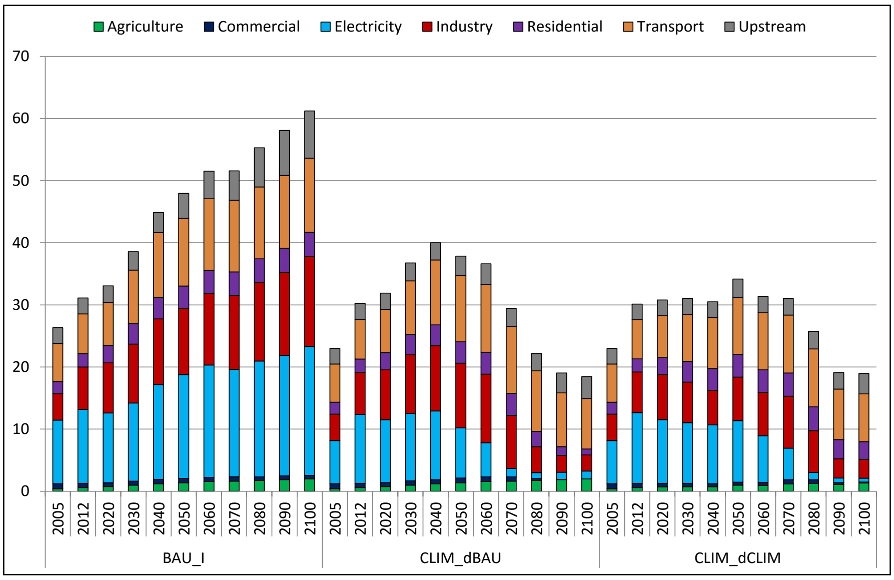


Figure 4.2 World CO_2e emissions by sector (Gt)

In the CLIM_dBAU scenario, the CO_2 emitted by the electricity sector decreases from around 7 Gt in 2005 to 1.2 Gt in 2100. CO_2 emissions reach 0.6 Gt in 2100 in the CLIM_dCLIM scenario. CO_2 emissions represent nearly 21 Gt in 2100 in the BAU. The electricity sector share of total CO_2 emissions moves from 30% in 2005 to 7% and 3% respectively in CLIM_dBAU and CLIM_dCLIM. While CLIM_dCLIM appears more stringent in terms of decarbonisation for the electricity sector, it is interesting to note that the CO_2 emissions mitigation in the industry is more important in CLIM_dBAU than in CLIM_dCLIM with 2.6 Gt of CO_2 emitted in 2100 in the former against 3 Gt of CO_2 emitted in the latter scenario. CO_2 emissions in industry in 2100 represent 14% in CLIM_dBAU and 16% in CLIM_dCLIM of the total CO_2 emissions (24% in BAU) against 19% in 2005.

Other sectors impacted by the climate policies implemented in the scenarios are commercial and residential. In the BAU, these sectors account for 1 and 6% respectively of the CO_2 emissions in 2100 (3% and 7% in 2005). In CLIM_dBAU, they represent near to zero and 5% respectively for commercial and residential sectors in

2100 and 1% and 16% respectively in CLIM_dCLIM at the same period. The CO_2 emissions in the commercial sector move from 0.8 Gt in 2005 to 0.007Gt in 2100 (0.1 Gt in CLIM_dCLIM and 0.5 Gt in BAU) in 2100. Note that in the BAU, the CO2 emissions from the commercial sector are less in 2100 than in 2005. As regard the CO_2 emissions in the residential sector, they reduce from 1.9 Gt in 2005 to 0.9 Gt in 2100 (2.8 Gt in CLIM_dCLIM and 3.9 Gt in BAU in 2100).

These results suggest that the transport sector will be the most difficult sector to decarbonize. Indeed, impact on the transport sector is less important and the CO_2 emissions mitigation in the climate scenarios is quite limited compared to the BAU, with an ever increasing path of CO_2 emissions in climate scenarios even if slower than in BAU. On the other hand, the decarbonisation of the other sectors involves than the CO_2 emissions from transport sector represent more than 40% in 2100 in the climate scenarios by comparison with 19% in the BAU.

4.3.3 DISCUSSION

This coupling tentatively shows that modellers can benefit from information on the whole economy with the representation of factor markets (capital, labour) from a Macro model on the one hand, combined with technology richness of the BU models, which represent better the technologies available in a specific bounded economy for a given time. Nevertheless, the models do not necessarily converge due to the difference in structural design and modelling paradigm. Some technical and mathematical challenges need to be addressed to provide insights into policy recommendations. The applied methodology presents some limitations in terms of indicators harmonization and prices consistency and results should be interpreted with care. From a microeconomic point of view, a major difference residing in TD and BU models is that the behaviours of both energy suppliers and end-users may affect significantly the general equilibrium and underlying prices on the different markets; these in turn will have repercussions on the investment and savings decisions across regions. Also, the government's fiscal policies play a central role in boosting or slowing the economic growth and influence all the institutions of the market.

4.4 FOCUS ON CHINA WITH ETSAP-TIAM AND AIM

China's economy and energy system developed rapidly since the 1980s, followed by an increase in CO_2 emissions. Analysing pathways for China's future development and associated global issues relies on complex global modelling tools that incorporate sufficient sub-regional details of China. Recent modelling exercises that account for such global and sub-regional economy and energy system features are however rarely described in the peer-reviewed academic literature (Mischke and Karlsson, 2014).

This China soft-linking case study aims to bridge this knowledge gap between existing global and China-specific scenario studies, which are currently carried out by different academic institutions with multiple modelling tools (Mischke and Karlsson, 2014). One example of a such a modelling exercise for China was carried out by (Chen, 2005). Using a hybrid MARKAL MACRO model for China, (Chen, 2005) concluded that the economic costs of a carbon emission reduction pathway in China towards 2050 are rather high, estimated at up to 2.54% of GDP loss.

The soft-linking of a global TD economic model, the Asian-Pacific Integrated assessment Model (AIM/CGE) developed in the National Institute of Environmental Studies of Japan (NIES), with a global BU energy system model, the ETSAP-TIAM model with sub-regional China features developed in the Technical University of Denmark (DTU), is carried out here to establish a common global and China-specific reference scenario. On this basis, global, China national and China sub-regional economic, energy and emission pathways can be documented, analysed, and replicated simultaneously.

4.4.1 *METHODS*

The two global optimization models are expanded with a sub-regional level of detail for China as per the country's regional geographic definitions of the 7th Five Year Plan (National People’s Congress, 1985). Both models represent the economy and energy system of 16 world regions plus China. China-specific base year data are calibrated against official Chinese government statistics, including provincial energy balances and input-output tables. The global AIM/CGE model represents moreover up to 30 provinces of China, with 22 economic sectors and three final demand sectors (Dai et al., In Review). A triangulation method to integrate provincial energy statistics for China into ETSAP-TIAM (Loulou and Labriet, 2008) was established (Mischke, 2013).

The soft-linking approach used in this study comprises the following three major steps, which are similar to other country case studies presented here:

1. Step 1: TD to BU

   The AIM/CGE model provides initial inputs for the ETSAP-TIAM model for a direct or indirect linking of the sectors in both models. The outputs of the economic sectors from the AIM/CGE model are used as drivers for energy service demand in ETSAP-TIAM model. If required, alternative projections from other sources are used, such as population statistics.

2. Step 2: BU to TD

   After ETSAP-TIAM calculates the optimal technology mix and final energy demand in different sectors, the energy efficiency parameters of the AIM/CGE model are adjusted so that the energy consumption matches the ETSAP-TIAM results.

3. Step 3: Model iterations

   After these two steps, equivalent to the first iteration, the results of energy service demand in the AIM/CGE model might change. If the change in parameters is significant, new iterations are carried out until an acceptable convergence is found. The hybrid model developed in this study is named CGESL.

Common reference scenario

A common reference scenario is constructed and tested in various iterations. It follows the GDP and demographic trends of a newly developed, moderate Shared Socio-economic Pathways (SSP2) scenario (O'Neill et al., 2014). The SSP2 pathway is downscaled for China, following the principle that the existing socio-economic disparities within China will be narrowed towards 2050. Future GDP growth projections for China and other model regions are thus a main driver in both models. GDP pathways of East-, Central- and West-China are summarised in Table 4.1.

Region	2005	2010	2020	2030	2040	2050
East-China	1.0	1.5	3.5	6.5	9.8	12.3
Central-China	1.0	1.5	3.9	7.5	12.1	15.8
West-China	1.0	1.5	3.7	7.0	11.1	14.4

Table 4.1 Future economic growth increase for sub-regions of China under SSP2 (2005=1)

4.4.2 Reference scenario results

At a **global level**, the hybrid model (see Figure 1, marked in green) shows a 2-2.5 times increase in global power production, primary and final energy use and CO_2 emissions towards 2050. The pathway for final energy is thereby highly harmonised between the different modelling tools. The AIM/CGE model and the ETSAP-TIAM model (see Figure 4.3, marked in red and blue), if used stand-alone, diverge increasingly in their pathways for global power production, primary energy use and global CO_2 emissions.

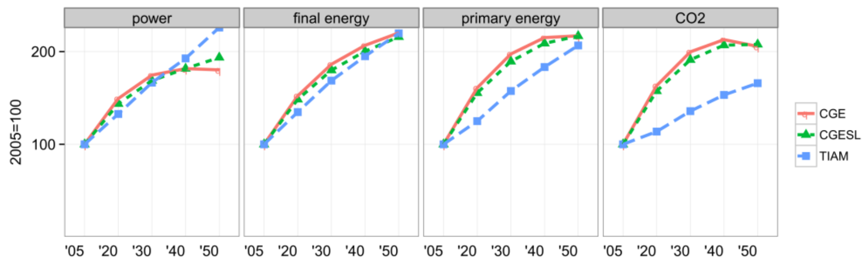


Figure 4.3: World reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models – pathways for power generation, primary and final energy use, and CO_2 emissions towards 2050

At a **China national level**, the hybrid model (see Figure 4.4, marked in green) shows a 5 times increase in China's power production, primary and final energy use and CO_2 emissions towards 2050. A peak in these pathways is suggested around 2040 in the TD AIM/CGE and the hybrid CGESL model, however not in the BU ETSAP-TIAM model. As described above, the stand-alone models diverge increasingly towards

2050. While the TD AIM/CGE model calculates an almost 6 times increase in all pathways towards 2050, the BU ETSAP-TIAM model calculates a much lower rate of increase of about 3-5 times.

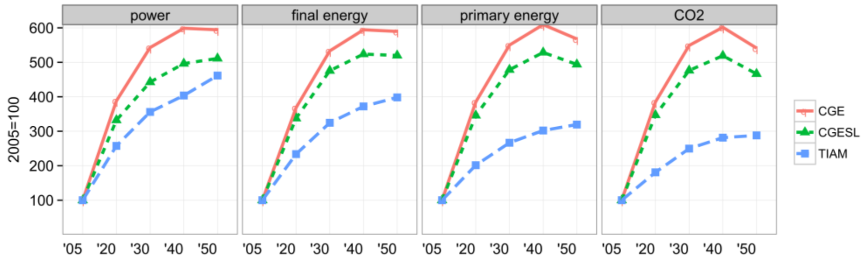


Figure 4.4: China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models – pathways for power generation, primary and final energy use, and CO_2 emissions towards 2050

Analyzing the modelling results for the **East-China sub-region**, which summarizes the highly developed coastal provinces of China, provides the further insights. The hybrid CGESL model (see Figure 4.5, marked in green) shows a 3.5-4 times increase in East-China's power production, primary and final energy use and CO_2 emissions towards 2050. A peak around 2040 is suggested in most pathways studied here, similar to the national-level results for China. As discussed before, the stand-alone models diverge.

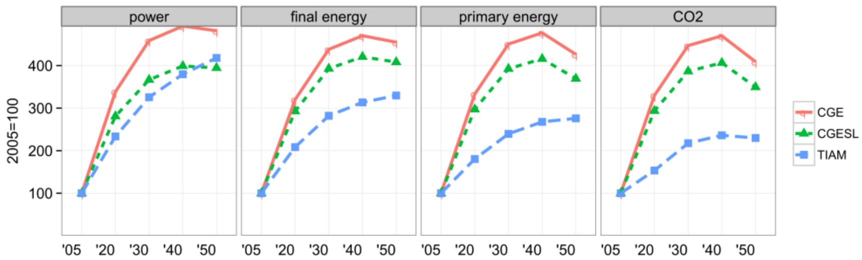


Figure 4.5: East-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models – pathways for power generation, primary and final energy use, and CO2 emissions (2005-2050)

The pathways for the **Central-China sub-region**, which comprises many resource-rich provinces of China, are provided in Figure 4.6. The hybrid CGESL model (see Figure 4.6, marked in green) indicates a 6-6.5 times increase in Central-China's power production, primary and final energy use and CO_2 emissions towards 2050.

The divergence in the pathways of the TD and BU models is highest for CO_2 emissions: the maximum increase in CO_2 emissions between 2005 and 2050 is about 7 times in the TD AIM/CGE model and only about 3 times in the BU ETSAP-TIAM model.

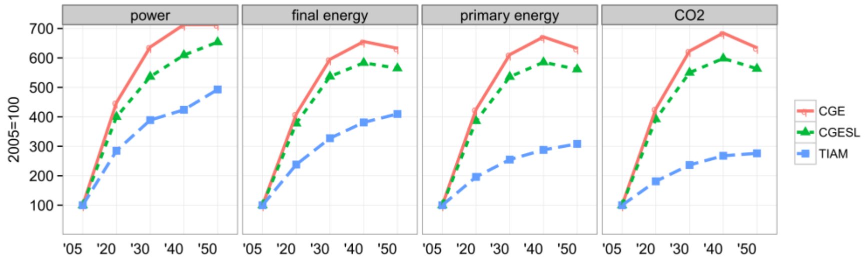


Figure 4.6: Central-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models – pathways for power generation, primary and final energy use, and CO2 emissions towards 2050

The **West-China sub-region** comprises many sparsely populated and economically less developed provinces of China. The corresponding future pathways are provided in Figure 4.7. The results are similar to the other sub-regions of China, indicating major differences if models are not soft-linked and used stand-alone under a common reference scenario.

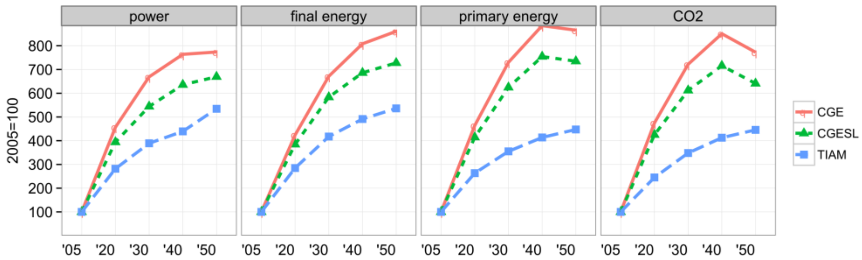


Figure 4.7: West-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models – pathways for power generation, primary and final energy use, and CO2 emissions towards 2050

4.4.3 Discussion

Soft-linking global models with regional China features allows for new, sub-regional insights into China's future economic and energy system development. The common reference scenario established and tested in this study could provide a basis for future scenario studies about the potential global impacts of China-specific sub-regional and national energy and climate policies. These results, if replicable, reliable and transparent, could feed into an ongoing energy and climate policy debate in China, which is striving to balance global and China-specific regional development issues.

As previous scenario studies for China showed, the divergence in China-specific scenario results calculated by different modelling tools with different underlying assumptions is rather high (Mischke and Karlsson, 2014). Our preliminary results confirm that China-specific modelling exercises should be sufficiently harmonised and documented first, before applying any modelling framework to study policy scenarios for China in a global context.

To cope with the range of uncertainty in China's future energy and emission projections, future work should focus on benchmarking such a global and China-specific modelling exercise with more leading global and China-specific scenario studies. More research is also needed to understand and explore uncertainty in underlying statistical differences that serve as inputs for this and other modelling frameworks.

4.5 Focus on South America with TIAM-ECN and E3ME

Within the framework of the European research project CLIMACAP[8] the global energy system model TIAM-ECN and the global macro-economic model E3ME are linked in order to enhance the energy and economic analysis capabilities focusing on Latin American energy topics.

TIAM-ECN is the TIMES Integrated Assessment Model (TIAM) of the Energy research Centre of the Netherlands (ECN), used for long-term energy systems and climate policy analysis. It has a global scope with a world energy system disaggregated in 20 distinct regions. TIAM-ECN is a linear optimisation model, based on energy system cost minimisation with perfect foresight until 2100. It simulates the

[8] www.climacap.org

development of the global energy economy over time from resource extraction to final energy use.

E3ME is an econometric input-output model of the global economy, energy system and environment. It is maintained and developed by Cambridge Econometrics (CE), and is frequently applied to assess the macroeconomic impact of energy policies and technologies, as well as other energy-environment-economy (E3) interactions. In the CLIMACAP project it is applied as a tool to assess the impact of whole energy system scenarios on the wider economy of selected Latin American countries. The model uses a combination of accounting identities and empirically estimated econometric equations to assess the impact of these different energy system pathways on consumers, industries and the economy as a whole. Importantly, E3ME includes a technology defined approach to modelling the power sector, and therefore the scenarios can be made compatible with TIAM-ECN.

4.5.1 Methods

The two models are aligned in the sense that, first, they apply consistent assumptions for global parameters, including fossil fuel prices, carbon prices, technology efficiency and technology costs. Secondly, that the results from the TIAM-ECN model, including capacity and generation figures, energy demand and required investment costs, define model input data that is fed into E3ME. Energy sector results from TIAM-ECN are processed and input to E3ME including:

- Electricity capacity and generation development, by power sector technology;
- Hydrogen capacity and generation development, by hydrogen sector technology;
- Industrial energy consuming technology (production method) CCS capacity;
- Energy demand, by final user and fuel type;
- Energy system investment costs, by technology type;

These inputs are processed before being used in E3ME to convert to the required units of measurement and classifications. As the TIAM-ECN model is solved every 10 year interval to 2050 (focus in CLIMACAP project on horizon until 2050) and E3ME requires annual inputs, the figures for the intermediate years are interpolated from the TIAM-ECN results.

As explained above, a change in electricity prices is modelled in order to account for changes in the cost of power sector investment, transmission costs and CO_2 capture and storage. In all other cases it is also assumed that there is an increase in prices to finance the energy technology investment. There is an increase in prices in the industries that invest in carbon capture and storage (CCS) technology to fund investment in industry CCS. It is assumed that there is an increase in the price of vehicles that is sufficient to cover the investment cost to finance additional investment in vehicles.

Electricity prices, energy system investment, prices of energy-using capital, and fuel demand determine the overall economic impact. There are three channels through which the TIAM-ECN results impact on the economy:

- through the level of investment in energy technologies, and the upstream impact of that investment,
- through the electricity prices and industry costs, and the consequential impact on demand,
- through the mix of energy demand by fuel in the economy and the associated trade balance.

4.5.2 RESULTS

The results in Figure 4.8 show on the left side energy technology expenditures for Latin America and representative selected countries, and on the right side the corresponding macro-economic impact in term of GDP change decomposed by their main effects. The results refer to a scenario with a carbon tax on GHG starting at US$ 50 in 2020 and increasing by 4% per year in real terms. The change of GDP is given versus the baseline development which does not impose any climate policy measures for the future.

For the macro-economic modelling with E3ME a dominating investment effect can be observed for Latin America. The investment is paid for, ultimately, by consumers who see an increase in real household consumption[9]. In net terms, GDP increases by 1.6 % in 2030, 2.0 % in 2040 and 1.3 % in 2050. The main driver for this dynamic is the shift in the structure of the economy, from fossil fuel supply chains to capital supply chains, which leads to stronger dynamic multiplier effects. A closer look at investments shows for Latin America as whole, and in particular for Brazil and Mexico, that additional investment in the power sector does not crowd out investment in the rest of the economy, since investment in productive assets is not constrained, because it can be withdrawn from investment in non-productive assets. As a result, the impact on GDP in E3ME is a net effect of the increase in investment. In principle, the positive investment impact could outweigh the negative price effects reducing real consumer spending since E3ME allows for spare capacity in the labour market and so demand-side (investment) stimulus can yield positive GDP results. Since many consumer goods are imported, the reduction in consumption leads to a reduction in imports which also impacts on GDP. For Mexico the net impact on GDP mostly reflects two competing factors in the longer term driven by the changing structure of the energy system. As more capital and less fuel intensive technologies come into the energy system a demand for these capital goods (investment) is offset by the extra price of these technologies. The technology outcome matters considerably in the determination of the results, in particular the overall cost and the relative weighting of the capital and operating cost components and the characteristics of those supply chains in the domestic economy. In the early period, the investment effects dominate substantially, but by 2050 the differences are much smaller and the net impact on GDP is only around 1% at a CO_2 price of \$165/tCO2 and emissions reductions of over 50% compared to the baseline. Consumer spending in 2050 is 0.4% higher than in the baseline due to the recycling of the carbon tax. Colombia´s total production could be positive with an increase of up to 2.7% by 2050,

[9] In the modelling approach applied in this study the carbon tax revenues has been recycled to households.

with negative GDP impacts from increasing imports (to meet increasing demand) and reducing exports (as a result of the price effects). The developments of employment under the carbon tax scenario show an increase of employment compared to the baseline by almost 5 million (net additional) jobs (+1.4%) across Latin America by 2050. New jobs are created in particular in Brazil and in Argentina with a growth of more than 2% each.

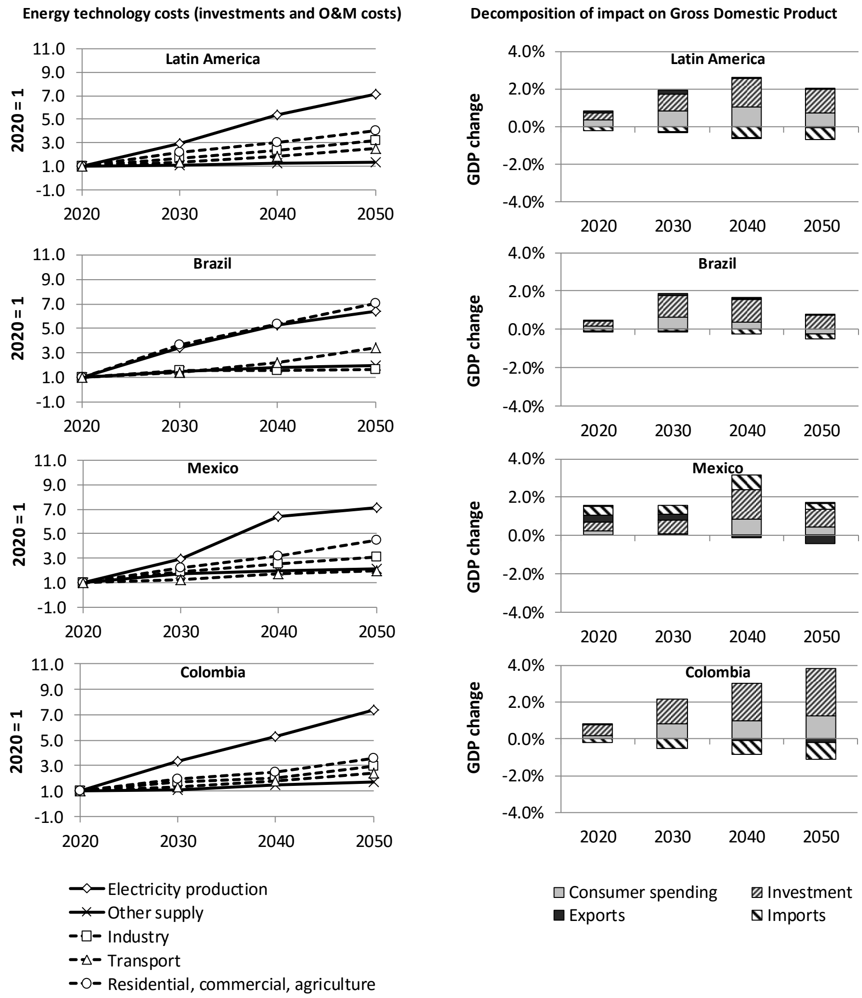


Figure 4.8 Energy investments and GDP impact on Latin America under a high carbon tax scenario

4.5.3 DISCUSSION

Comparing the results from the linkage of TIAM-ECN and E3ME with results from the CGE model, the consequences of increasingly higher carbon prices in terms of reduced consumer spending and GDP are linear in the CGE models and increase as the carbon price increases; but divergent and non-linear in the soft-linked modelling approach reflecting the explicit definition of physical characteristics of technology in

TIAM-ECN and the economic impact of the technologies different economic characteristics as represented in E3ME.

The model linkage approach captures detailed technology switching and this is reflected in the non-linearity of the economic results, but the model also yields different results because of fundamental differences in economic structure and approach that allow policies that stimulate the demand side to lead to positive impacts on GDP even in the long term. The outcome of the combined model approach shows that both investments and consumer spending will increase under climate policy, which suggests that the price impacts of more expensive energy due to structural changes to the energy system can be compensated by the impact of the related changes to the structure of the energy system and economy.

4.6 Acknowledgements

The authors wish to acknowledge the journals of Applied Energy and Climate Change Economics where relevant original research papers have been published (Dai et al., In Review; Labriet et al., In Review).

Chapter 5 ECONOMIC IMPACTS OF FUTURE CHANGES IN THE ENERGY SYSTEM – NATIONAL PERSPECTIVES

Glynn, J., Fortes, P., Krook-Riekkola, A., Labriet, M., Vielle, M., Kypreos, S., Lehtilä, A., Mischke, P., Dai, H., Gargiulo, M., Helgesen, P.I., Kober, T., Summerton, P., Merven, B., Selosse, S., Karlsson, K., Strachan, N., Gallachóir, B.Ó., 2015. Economic Impacts of Future Changes in the Energy System—National Perspectives, in: Giannakidis, G., Labriet, M., Gallachóir, B.Ó., Tosato, G. (Eds.), Informing Energy and Climate Policies Using Energy Systems Models, Lecture Notes in Energy. Springer International Publishing, pp. 359–387.

5.1 INTRODUCTION – REGIONAL APPLIED HYBRID MODELS

To reiterate the essence of this chapter, continuing from Chapter 4: global economic and environmental scenarios consistently show a trend of continuous decline in natural resource reserves, degradation of environmental quality, increasing vulnerability of economic growth as a result of environmental stresses, competition for natural resources, soaring energy prices, and climate change. These scenarios partly rest on significant efforts by the scientific community over the past three decades to improve knowledge of the interactions between economic growth and the environment; particularly, modelling methods have developed to become increasingly applied to the assessment of the environmental and economic consequences of various energy and greenhouse gas (GHG) policies. Policy makers need clear and consistent information concerning the real impact of energy and climate policies on the economy and the most cost-effective technology portfolio to achieve their goals. Separate use of top-down (TD) and bottom-up (BU) models do not adequately address all these aspects, which might lead to ineffective policies.

Hybrid models, that combine the technological detail of BU models with the economic framework of a TD, e.g. General Equilibrium (CGE) models, have been developed as an alternate method. Despite the extensive literature on hybrid models, there are few quantitative examples employing a 'full-link' (i.e. not focusing on only one sector) and 'full-form' BU and TD models. This chapter outlines several hybrid models considering both full-link, full form, and sectoral model developments as well as hard-linking MARKAL and TIMES MACRO models. All models presented are applied nationally within the Energy Technology Systems Analysis Programme (ETSAP) Community. The general rationale, motivation for regional and global model development are summarised in Chapter 4. This Chapter, Chapter 5, focuses on the first national decarbonisation legislation, theoretical model updates, improvements, and lastly learning outcomes from applying methods to national models.

5.2 Evidence based UK climate legislation using hybrid models

The energy modelling research community has long underpinned energy policy (Jebaraj and Iniyan, 2006), in providing insight and numerate policy guidance (Huntington et al., 1982). The United Kingdom (UK) was the first government to legislate for mandatory GHG reduction targets, first aiming at a 60% CO_2 reduction by 2050 relative to 1990 (BERR, 2007). The ETSAP hybrid UK MARKAL-MACRO (UK MM) model was used extensively to provide the evidence base to guide discussion in the first iteration of analyses and represented a significant addition to UK energy-economy modelling capacity (DEFRA, 2007; FES, 2003; Strachan and Kannan, 2008). UK-MM is a BU optimisation method that maintains sectoral technological detail, but endogenises aggregated price- dependent energy service demand dynamics via the single- sector neoclassical growth model. It is the first step in assessing the competing elements of hybrid energy modelling: technological explicitness, microeconomic-realism and macroeconomic completeness (Bataille et al., 2006). It gave insights while public debate was still ongoing as to the costs, benefits, opportunities and energy security concerns of climate change under long term uncertainty (Nordhaus, 2007; Pearce, 2003). UK climate policy had been primarily driven by scientific and political competition (RCEP, 2000; Stern, 2006), while macroeconomic impact was not a significant concern in the short term. The UKERC UK-MM studies showed that the short term impacts were manageable (Strachan and Kannan, 2008). This enabled public and policy discussion to focus on sector specific impacts, social impacts and industrial effects. Further, it moved the policy discussion from whether the UK should decarbonise or not, to how to decarbonise. Four subsequent studies combined modelling effort of the AMOS, E3MG, MDME3 and MARKAL-MACRO models to continue to assess the technical feasibility of the 60% CO_2 reduction target, finding critical technologies and reducing uncertainty (Allan et al., 2012, 2007; Strachan et al., 2009). These modelling activities highlighted the critical nature of developments in the power sector, marginal technologies, resource availability, the cost of carbon, and behaviour in relation to the potential impact upon economic activity (GDP). As a result of the 2008 climate change act, the climate change committee was founded, providing legally binding carbon budgets for the UK, and is investigating stronger measures of 80% CO_2 reductions, beyond the power sector, by 2050.

In the wake of the 2008 economic crisis, with the resultant austerity measures, risk aversion, and reduced investment capital, implementing the carbon budgets have been more difficult than initially expected. In previous studies, ex-post analysis has shown errors in model forecasting in the EU (Pilavachi et al., 2008), and US (Winebrake and Sakva, 2006), and notes particular care should be taken to avoid model bias entering energy policy when energy models are directly applied by policy makers (Laitner et al., 2003).

5.2.1 Modelling Method Summary

Like TIMES, MARKAL is a dynamic, technology rich linear programming (LP) energy systems optimisation model. Its objective function minimises total discounted costs, including capital, fuel and operating costs for resource, process, infrastructure, conversion and end use technologies. It is a partial equilibrium model with perfect foresight. MARKAL was extended with a hard-link to MACRO. The objective function of the hybrid model is the maximisation of the discounted log of utility summed over all periods (t) with an end of horizon terminal investment term. Utility is derived as the log of consumption. National production is from energy, capital and labour, substitutable in a nested constant elasticity of substitution (CES) production function. Capital and labour substitute directly for each other based on optimal capital value shares in their aggregate. Aggregated capital and labour is substitutable with a separate energy aggregate. Investment is recycled to build up a depreciating capital stock, while labour growth rates are defined exogenously.

The marginal change in production output is equivalent to the cost of changing its energy demand. This allows heterogeneous energy demand adjustment across sectors dependent upon marginal demand costs. However, shadow price responses need to be smooth to ensure marginal demand responses are realistic and allow model convergence. Autonomous energy service demand adjustment enables useful climate scenario analysis of demand responses that are decoupled from economic growth. A technical summary of the TIMES-MACRO model formulation follows in section 5.3, while further technical detail of the UK-MM is available in (Strachan and Kannan, 2008).

5.2.2 EVIDENCE BASE FOR POLICY

54 low-carbon "what if" scenarios were modelled with UK-MM to advise the UK energy white paper of potential costs of differing technology development pathways in a future with a 60% reduction in CO_2 emissions (BERR, 2007). The summary results are clustered into 4 representative scenarios, focusing on insights from the hybrid linkage, the timing of emissions constraints trajectories, fossil fuel costs and technology abilities (Strachan and Kannan, 2008). The macroeconomic impact of the future changes to the UK energy system are summarised as percentage loss of projected GDP in Table 5.1. There is significant technical change across all sectors in all base case scenarios – before carbon constraints are applied - with car stock switch to hybrid vehicles and implementation of energy efficiency measures in building energy conservation. In the medium to long term (2030 – 2050) energy efficiency opportunities are exhausted and final energy demand grows, even with MACRO feedback. Higher or lower fossil fuel prices lead to lower (8%) or higher (3%) energy consumption respectively in 2050.

MARKAL-MACRO Scenario run	% GDP Loss			
	2020	2030	2040	2050
Central Scenario	0.46	1.7	2.43	2.81
With accelerated technological change	0.45	1.6	2.35	2.58
With higher fossil fuel prices	0.45	1.54	2.27	2.64
With accelerated energy efficiency	-0.07	0.63	1.63	2.04

Table 5.1 UK MARKAL-MACRO scenario analysis summary results

In carbon constrained scenarios, decarbonising the electricity sector is seen as the best technology pathway without behavioural change and demand adjustments, while allowing greater electricity consumption. The additional flexibility of demand endogeneity through MM is critical in accurately assessing the marginal cost of carbon. In MM 60% CO_2 reduction scenarios, energy efficiency and conservation is maximised, with 10-15% reductions in individual energy demand (compared to standard MARKAL runs) contributing considerably to lowering marginal CO_2 prices. In the short term, it is noted that all carbon constrained scenarios have relatively benign impact upon GDP, while accelerated energy efficiency policies can have positive economic benefits via energy cost savings leading to increasing alternative consumption. It is also noted that while there is a significant loss of GDP in the range of 2% - 2.8% GDP in the long term to 2050, this impact is not seen as insurmountable. The marginal CO_2 price of the central scenario rises to €147/tCO_2 (\$189/tCO_2), while this price is estimated at €189/tCO_2 (\$243/tCO_2) without endogenous demand reductions from MM.

5.2.3 *Discussion*

UK energy policy makers have recognised the insights generated by hybrid energy-economy, giving GDP and demand responses to energy system decarbonisation. Relevant policy makers were educated in formal energy-economic analysis and how to interpret decarbonisation scenario analysis results. Key staff members of the Committee for Climate Change were on the original UK-MARKAL project steering group. The additional flexibility of the MM demand endogeneity is seen as critical in estimating the marginal cost of carbon. There are notable trade-offs between optimum technological decarbonisation pathways and the impact that behaviour has on the marginal technology choices.

While seen as manageable, the cost impacts from the UK MM model are likely to underestimate the cost of CO_2 mitigation as a result of the lack of regional trade competitiveness or transitional effects. This is observed when comparing results from the studies in section 5.3, and section 2 – Chapter 4. Decarbonising faster than other nations creates a competitiveness disadvantage that UK MM does not account for. As a result, inter-regional hybrid models are critical to account for global trade and competitiveness effects. Further experience from policy engagement sees the requirement for more detailed disaggregation of hybrid models to investigate spatial and socio-demographic effects. An extended treatment of natural capital stocks within nested CGE models is required to investigate realistic substitutability between natural and conventional capital as factors of production. A final lesson learned from the UK policy experience is the need for greater modelling transparency to enable replication of results. A comprehensive global hybrid model is summarised in Chapter 4 section 2. First however, the theory behind the MACRO and MSA models – the work of Socrates Kypreos and Antti Lehtilla - are outlined in the following section 5.3.

5.3 TIMES-MACRO STAND ALONE

Computer based models representing energy, economy and environmental interactions are specified, among others as non-linear (NL) optimization problems or as computable general equilibrium (CGE) simulation models (Arrow and Debreu, 1954). Optimization models when satisfying some maximization conditions give the same solution as CGE models (Capros et al., 1997). The multiregional bottom-up energy system model TIMES (Loulou et al., 2005), linked with the top-down macroeconomic module MACRO called TIMES-MACRO (TM) (Remme and Blesl, 2006), is solved by maximizing an inter-temporal utility function for a single representative producer-consumer agent in each region. TM has been developed as part of the Implementing Agreement of the Energy Technology Systems Analysis Project (ETSAP) of the International Energy Agency to assess, among others, the whole energy system and climate change mitigation options and policies on the national, multiregional or global level. The multiregional TM models, large in size, are not solvable with direct NL optimization methods even when the most powerful commercial solvers and state of the art computers are used. On the other hand, a similar in size and structure model, the well-known MESSAGE-MACRO of IIASA (Messner and Schrattenholzer, 2000), is successfully and efficiently solved by decomposition methods. The mathematics to decompose and solve TM with an iterative algorithm is outlined below. The decomposition method converts TM to an energy part (TIMES) and a small size NL macroeconomic model, called TIMES-MACRO Stand-Alone (TMSA), where the energy model TIMES is substituted by appropriate quadratic cost supply functions (QSF). This outline continues to describe the demand projections for TIMES and explain the multiregional TMSA, the Negishi (1972) welfare function, and the iterative procedure applied to solve the problem based on the sequential equilibrium algorithm of Rutherford (1992) (Negishi, 1972; Rutherford, 1992). Finally the performance of the algorithm is explained and some resultant conclusions discussed.

5.3.1 Energy Service Demand Projections

The ETSAP family of models defines demands that reflect past trends and exogenous assumptions on population, GDP, energy intensity and technology penetration based on demand drivers and their elasticities. As most of the efficiency improvement options are included in the engineering model explicitly, and are selected if they make economic sense, the specific selection of autonomous energy efficiency improvement factors (*aeeif*) applied below could be introduced to reflect mainly life style changes. A simple but useful relation for demand projections is the following:

$$\frac{D_{it}}{D_{i0}} = \left[\frac{dr_{it}}{dr_{io}}\right]^{\alpha_i} \cdot \left[\frac{P_{it}}{P_{i0}}\right]^{-\sigma_i} \cdot \prod_{\tau=1,t} (1 - aeeif_{i\tau})^{ypp_\tau} \qquad (1)$$

Here, D_{it} is the demand projection for sector i and period t; D_{i0} is the same demand for the starting year calibrated to energy statistics in line with the socio-economic assumptions and the efficiencies of the end-use devices valid in the starting year of analysis; dr_{it} is the demand driver; α_i the driver elasticity; σ_i the price elasticity; $aeeif_{it}$ the autonomous efficiency improvement factor per demand category; ypp_τ the years per period; and P_{it} / P_{i0} the index of relative price of demand in sector i. TIAM (the global multiregional integrated assessment version of TIMES) assumes different growth rates and elasticities of demand drivers for each individual demand category. Usually some consistency checks of economic assumptions and the projections generated based on the equation above must be completed. IIASA for example adjusts projections to the results of MERGE (Manne et al., 1995), while ETSAP uses GEM-E3 (Capros et al., 1997).

5.3.2 *The multi-regional TIMES-SA model*

In the following section the global and multi-regional macroeconomic growth model is decomposed into a multi-regional partial equilibrium energy problem, e.g. TIMES, and a multi-regional macroeconomic model maximizing the global welfare function.

5.3.2.1 *The Macro Stand-Alone Formulation (MSA)*

For the new stand-alone Macro formulation, the original Macro model had to be generalized to support multiple regions. In the multi-regional case the model is solved by maximizing the Negishi-weighted sum of regional utilities based on iterations between the stand-alone TM model (TMSA) and the standard TIMES model. The TMSA model explicitly considers only the trade of the numéraire good, as the trade in all energy products is defined in the TIMES model. The basic formulation of the original TM implementation can be rewritten by the following equations (2)–(11):

$$Max\ U = \sum_{t=1}^{T} \sum_{r} nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(C_{r,t}) \tag{2}$$

$$Y_{r,t} = C_{r,t} + INV_{r,t} + EC_{r,t} + NTX\,(nmr)_{r,t} \tag{3}$$

$$Y_{r,t} = \left(akl_r \cdot K_{r,t}^{kpvs_r \cdot \rho_r} \cdot l_{r,t}^{(1-kpvs_r)\rho_r} + \sum_k b_{r,k} \cdot DEM_{r,t,k}^{\rho_r} \right)^{\frac{1}{\rho_r}} \tag{4}$$

$$K_{r,t+1} = tsrv_{r,t} \cdot K_{r,t} + \frac{1}{2}(d_t \cdot tsrv_{r,t} \cdot INV_{r,t} + d_{t+1} \cdot INV_{r,t+1}) \tag{5}$$

$$K_{r,T} \cdot (growv_{r,T} + depr_r) \leq INV_{r,T} \tag{6}$$

$$DET_{r,t,k} = aeeifac_{r,t,k} \cdot DEM_{r,t,k} \tag{7}$$

$$EC_{r,t} = qa_{r,t} + \sum_k qb_{r,t,k} \cdot (DET_{r,t,k})^2 + amp_{r,t} \tag{8}$$

$$\sum_r NTX(trd)_{r,t} = 0 \qquad \forall \{t, trd\} \tag{9}$$

$$aeeifac_{r,t,k} = \prod_{\tau=1}^{t} (1 - ddf_{r,\tau,k})^{\frac{d_t + d_{t+1}}{2}} \tag{10}$$

$$l_{r,1} = 1 \text{ and } \qquad l_{r,t+1} = l_{r,t} \cdot (1 + growv_{r,t})^{\frac{d_t + d_{t+1}}{2}} \tag{11}$$

Where

Cr,t : annual consumption in period t (variable)

Yr,t :annual production in period t (variable)

Kr,t :total capital in period t (variable)

INVr,t :annual investments in period t (variable)

DEM r,t,k :annual demand in Macro for commodity k in period t (variable)

DET r,t,k :annual demand in TIMES for commodity k in period t (variable)

EC r,t :annual energy system costs in Macro in period t (variable)

akl r :production function constant

amp t :constant term to account for the full annualized investment cost of existing capacities in the starting period.

b r,k :demand coefficient for demand commodity k

aeeifac r,t,k :autonomous energy efficiency improvement

dt :duration of period t in years

ddf r,t,kdemand decoupling factor (calibration parameter)

depr r :depreciation rate

dfact r,t :utility discount factor for period t

dfactcurr r,t :annual discount rate for period t

growv r,t :growth rate in period t (calibration parameter)

kpvs r :capital value share

l r,t : annual labor growth index in period t

nwt r :Negishi weight for region r

pwt, period-length-dependent weights in the utility function (to be introduced to in cases where the period lengths are not equal)

$qa_{r,t}$:constant term of the quadratic supply cost function

$qb_{r,t,k}$:coefficient for demand k in the quadratic supply cost function

$tsrv_{r,t}$:capital survival factor between periods t and t+1

ρ_r :substitution constant

T :number of periods in the model horizon

The primary differences in relation to the standard Macro formulation are; a) The use of Negishi weights in the objective function when the model is multi-regional; b) The inclusion of the trade in the numéraire good NTX(nmr) in the production function; c) The introduction of the trade balances on the global level (Eq. 9); d) The Negishi iterations balance for inter-temporal discounted trade deficits of a region over the full time horizon of the analysis; e) The replacement of the full TIAM LP cost accounting by quadratic supply-cost functions for each demand commodity (Eq. 8).

5.3.2.2 *The Standard TIMES LP Formulation*

The second part of the decomposed model, the TIMES LP model, uses the standard TIMES formulation, which can be written in short as:

$$Min\ NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \cdot ANNCOST(r,y) \tag{12}$$

$$A \cdot x = b \quad \text{and} \quad x \geq 0 \tag{13}$$

where:

NPV : net present value of all energy system costs

YEARS :the set of years within the model horizon

REFYR :reference year for discounting

$d_{r,y}$:capital discount factor for region r in year y

ANNCOST(r,y)annual energy system cost in region r and year y

A :coefficient matrix for all other model equations

x :vector of all model variables

b :RHS constant vector for all other model equations

R :number of internal regions in the model

For a comprehensive treatment of the standard TIMES LP formulation, see Loulou et al. (2005). In order to make the LP formulation more analogous with the Macro objective function, the objective function of the standard TIAM code can be rewritten in terms of period-wise average annual costs and period-specific discount factors, as follows:

$$Min\ NPV = \sum_{r=1}^{R}\sum_{t=1}^{T} pvf_{r,t} \cdot AESC(r,t) \tag{14}$$

where:

pvf r,t :present value factor for period t in region r

AESC(r,t) :annual energy system costs in region r and period t

T :number of periods t in the model horizon

The general specifications of the decomposition algorithm are described by (Kypreos and Lehtila, 2013)

5.3.2.3 The Algorithm and its Performance

In both MACRO formulations, the use of the MACRO model for evaluating policy scenarios requires that the demand decoupling factors (*ddf*) and labour growth rates (*growv*) have first been calibrated with the baseline scenario and the corresponding GDP growth projections. The core part of the calibration procedure is the updating of the demand decoupling factors and labour growth rates between successive iterations of the calibration algorithm.

In the TMSA implementation, all the basic mathematical formulas for the initial specification and updating the demand decoupling factors and labour growth rates are fully equivalent to those in the standard TM formulation introduced first by Kypreos (1996). The TIMES-MACRO documentation (Remme and Blesl, 2006) contains the details on the calibration algorithm and follow the description of Kypreos and Lehtila (2013) in the ETSAP documentation (Kypreos, 1996; Kypreos and Lehtila, 2013).

The initial Negishi weights are proportional to the regional output share while the updated ones balance for inter-temporal trade deficits following the sequential optimization algorithm of Rutherford (Rutherford, 1992). The weights are adjusted using the normalized price of the traded products, the trade excess and the inverse of the marginal regional utility and in that case, according to Rutherford the solution obtained is Pareto optimal.

$$NW_r = \sum_{t,trd} \pi_{trd,t} \cdot NTX_{r,t,trd} + \sum_t \pi_{nmr,t} \cdot C_{r,t} \text{ with } nwt_r = NW_r / \sum_r NW_r \quad (15)$$

One significant test run for the algorithm was the solution of TM for a single region as the problem could be solved with a direct optimization and the decomposition method and results are directly comparable. The USA TMSA model validated well against the direct solution of the TM of USA, as solutions are identical. However, the decomposed problem needs 2 minutes to be solved while the direct optimization takes more than 100 times longer. It is interesting to report the computer time needed to solve the calibration and the policy analysis case as function of the number of regions. The model starts in 2005 and covers up to 2060 in 7 time steps. A 6-region model takes about 32 minutes to be solved; a 10-region model needs 66 minutes and finally a 15-region model takes 100 minutes.

5.3.3 CONCLUSIONS

The large scale general equilibrium growth model TIMES-MACRO is solvable only when decomposed to the linear energy model TIAM and a non-linear macroeconomic stand-alone model (TMSA), where quadratic supply functions substitute for the energy system represented in TIMES.

The methodology is presented herein that allows projecting demands for energy services for a set of socio-economic assumptions, life style changes and energy intensities based on sectoral drivers, and its income and price elasticities. The regional demand decoupling factors (*ddf*) are introduced to calibrate the baseline case reproducing the same demands, although the MACRO model uses unitary income elasticity and the same elasticity of substitution across all sectors. The TMSA model then, including these decoupling factors, simulates the postulated GDP growth and the demands for energy. This is done with a minimum investment in respect of computation time. The execution times needed for low tolerance errors (less than 10^{-4}), is significantly reduced during both the calibration itself and when applying the model for a policy case. This can be done for either a single country model or for the multiregional and global TM model.

Although the quadratic supply cost function is a simple and approximate meta-model that substitutes for the full-scale energy model and the marginal prices are sensitive to small demand changes, the algorithm is able to give an exact calibration for the baseline case followed by good results for the carbon constrained case as the tolerance error in demand evaluation is below 10^{-4}. The prerequisite for a successful application of the QSF in representing energy and economy interactions is to have all the important system constraints determining the changes of the energy system linearized and included in TIMES. This is because the quadratic cost formulation allows for small changes around the demand variables when searching for optimal solutions and converges in small steps. For the first time the decomposition method proposed is able to solve the global TIAM-MACRO model with 15 regions in 1.5 hours based on TMSA (in Windows 7, 64-bit workstation, solution in a single thread).

5.3.4 IRELAND - APPLICATION OF TIMES-MACRO STAND ALONE

The hybrid linking of the Irish Energy system model, Irish-TIMES is taking a two pronged approach. First, the linkage and calibration of the newly developed Macro Stand Alone model to form Irish-TIMES-MSA. Secondly, a softlinking process is underway linking the National macroeconomic HERMES model to enable model comparison between the two approaches – aggregated production function and disaggregated sectoral production.

HERMES is a complete structural model of the Irish economy. The specification of the HERMES model is built on the assumption that firms are attempting to minimise their cost of production or maximise their profits and that households are attempting to maximise their utility. The energy system is no longer specifically modelled in the HERMES model. Energy is taken as an exogenously determined cost to firms and households through the international oil price (usually taken from NIESR's NiGEM model). Carbon taxation is incorporated in the government's financial accounts as a revenue source paid by firms and households. It is through oil and carbon pricing, both of which are exogenously determined within HERMES, that energy system costs feed back into the economy.

The initial Irish-TIMES-MSA results outline energy system pathways for a reference scenario (REF), a carbon constrained scenario with CO_2 reductions of 80% relative to 1990 levels (CO2-80), and an equivalent scenario with the macroeconomic impacts integrated into the analysis. The MSA scenarios cause a 10% reduction in final energy consumption by 2040 due to reduced demand as a result of increased energy system cost and a reduction of consumption in the economy. Interestingly, this alters the fuel mix most notably in the transport and residential heating sectors as carbon constraints become less binding and so fuel switching is delayed. The loss of GDP in the CO2-80 scenario rises to -1.5%/yr by 2050, with the CO2-95 scenario at -2.5%.

5.4 Portugal – HYBTEP

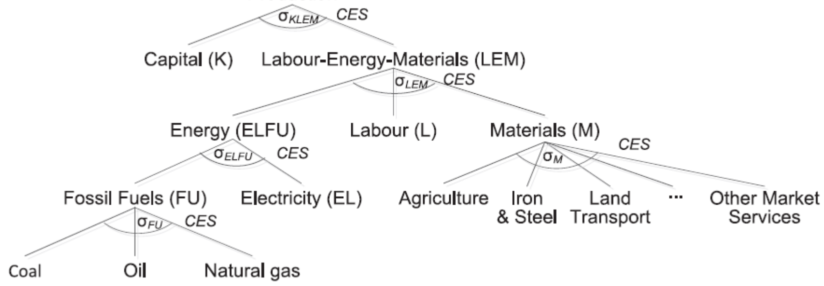
The lack of "full link", "full form" models integration in other modelling studies has been overcome by the development of an integrated methodology to soft-link the extensively applied BU TIMES model (Loulou and Labriet, 2008), with the CGE GEM-E3 model (Capros et al., 2014, 1997), used by several Directorates General of the European Commission. The hybrid platform, named HYBTEP (Hybrid Technological Economic Platform), applied to the Portuguese case, is defined by the soft-link between single country versions of the two models: TIMES_PT and GEM-

E3_PT (Fortes et al., 2013). HYBTEP overcomes the main limitation of CGE models – failure in represent technology choices – considering the energy profile and prices from TIMES, and minimizes the drawback of BU modelling – failure to represent adequately the link between energy and economy – as the changes in the sectors economic behaviour are set by GEM-E3 according to the BU technological choices.

HYBTEP was built by the following tasks, taking an approach close to (Labriet et al., 2010).

i. Defining coherence between the two models. Correspondence and harmonization between the models sets and variables were set up, namely the economic sectors and energy commodities. Additional energy carriers were also added to GEM-E3_PT, namely biomass. This process resulted in thirteen economic sectors in HYBTEP from the aggregation of eighteen sectors from GEM-E3_PT and more than sixty demand categories of TIMES_PT. Moreover, a crucial step to achieve consistency among the models is the definition of common scenario assumptions, namely fossil fuel import prices, interest rates, energy constraints and policy conditions.

ii. A new energy module in GEM-E3_PT was programmed allowing the model to receive exogenously the energy consumption by energy carrier and sector. This was done by assuming fixed shares of total energy demand per sector with a Leontief technology (i.e. elasticities of substitution of the Constant Elasticities Substituion (CES) production function equal to zero) (See Figure 5.1). These changes further implied alterations to the definition of the price of the energy aggregate, which are also set exogenously according to the BU model energy system costs evolution per energy aggregate (ELFU).



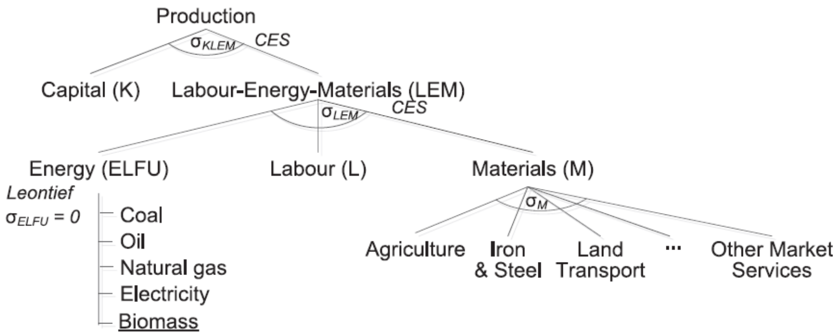


Figure 5.1 GEM-E3_PT computable general equilibrium nested tree structure (upper – a) Original GEM-E3_PT structure (lower - b) adapted Leontief structure in HYBTEP

i. The interaction algorithm (see Figure 5.1) and the conditions for convergence between the models require careful planning and definition. TIMES_PT physical energy consumption and system costs evolution per sector are 'translated' in GEM-E3_PT monetary units through an energy link module and inputted in the CGE model as energy demand and energy prices. In addition, GEM-EE_PT technological change, as measured as increased efficiency in the energy system was defined by the output of the BU model. When a market policy instrument is being considered in TIMES_PT, e.g. an energy tax or a feed-in tariff, the respective economic value is also included in GEM-E3_PT, associated with the respective payer and payee sectors. GEM-E3_PT than compute economic drivers, such as sector domestic production, which are converted in energy services demand through a demand generator. Energy services are inputted into TIMES_PT and the model sets the least cost technological profile of the energy system. This cycle establishes a single iteration of the linked models. It continues until convergence is achieved between the models results, which are reached by assuming a stopping threshold, reflecting minimal energy service demand differences from iteration n and the previous iteration (n-1).

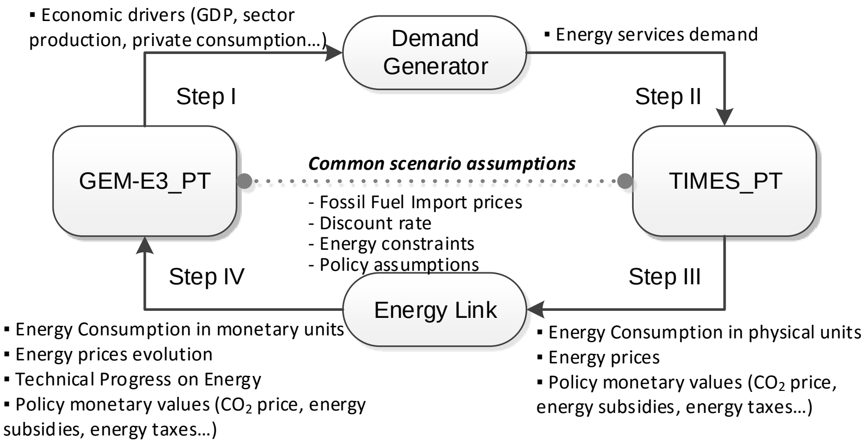


Figure 5.2 HYBTEP soft-linking methodology (Fortes et al., 2014)

The additional advantages of HYBTEP in assessing the impact of climate and energy policies when compared with conventional BU model, were analysed under the following scenarios modelled to 2050:

- Current Policy Regulation (CPR) extends beyond 2020, the current Portuguese energy-climate policy within the EU climate-energy package, including a reduction in GHG emissions, and an increase in renewable energy.
- CO_2 price scenario (TAX) comprises in addition to CPR assumptions, a domestic carbon tax on GHG energy emissions from 25€/t in 2020 up to 370€/t in 2050.
- RES support scenario (RES) involves, in addition to CPR assumptions, a monetary incentive to renewable energy, from 50 €$_{08}$/MWh in 2020 to 191 €$_{08}$/MWh in 2050.

For all the scenarios it was assumed in GEM-E_PT that a fixed government's deficit/surplus and additional revenues are recycled to the economy to reduce endogenously social security tax. In addition to HYBTEP platform runs, the policy scenarios were run by the standard TIMES_PT and by TIMES_ED, assuming an energy service-price elasticity of -0.3 for almost all demand categories, and a sensitivity analysis, considering higher (-0.5) and lower (-0.1) values.

5.4.1 RESULTS

The HYBTEP results show, that under TAX and RES scenarios, the modelling tools present differences regarding energy consumption and GHG emissions. It is not possible to define a linear relationship between HYBTEP results and TIMES elasticities, as these vary across scenarios and in some cases years. Under the TAX scenario, HYBTEP outcomes are close to TIMES_ED(-0.1) values, with differences below 1%. However, in the RES scenario the hybrid model reveals a lower endogenous elasticity, closer to TIMES_PT results.

In HYBTEP, the carbon tax induces an increase in production costs, but also represents a source of additional revenue to government. In this modelling exercise the income is recycled to the economy leading to a reduction in labour costs, which can partially offset the increase in energy costs in production. This economic framework, that result in a GDP loss of -2.4% in 2050 (versus a non-policy scenario), can justify the fact that HYBTEP is less responsive to energy prices than TIMES_ED(-0.3). In contrast, additional RES funding from the government means less available revenues to reduce social security contributions. The latter makes labour more expensive and outweighs the decrease in energy system costs due to energy subsidies. The fact that HYBTEP results are close to the inelastic TIMES_PT suggest that the reduction of energy prices are offset by an increase in labour costs, leading to a small impact on demand for energy services. In 2050, the RES scenario results in GDP gains of 2.8%, mostly driven by exports increase. Besides ignoring this comprehensive economic context, and with exception of the energy sector (e.g. power or refinery), TIMES neglects the linkages between the sectors, i.e., the intermediate consumption. Variations in the production price of one sector also affect domestic demand in other sectors production, which are not considered by the BU model.

Moreover, the sensitivity analysis of TIMES energy services elasticities highlights the impact of this parameter on the energy system profile. The BU model final energy consumption presented differences (TIMES_PT vis-à-vis TIMES_ED(-0.5)) of up to 14% and -12% in TAX and RES scenarios, respectively. The uncertainty of elasticity parameters, due to the lack of national studies, increases the uncertainty of the model results when comparing with a more transparent approach from HYBTEP.

5.4.2 DISCUSSION

HYBTEP represents an evolution in the methodological complexity describing a method of soft-linking 'full-form', multi-sector BU and TD CGE models, resulting in an integrated modelling platform. Since the main structures of the models are maintained, HYBTEP can accommodate an extensive group of technologies and contains a sector detailed economic matrix, considering sectors own characteristics and specificities. The major conclusion concerns the increase of transparency and accuracy of modelling outcomes achieved with HYBTEP, since, by assuming the economic framework of each sector, it enables understanding of the mechanisms behind energy demand evolution while taking into account the cost-effective energy profile from a technological model.

5.5 SWEDEN – TIMES-SWEDEN AND EMEC

The Swedish study describes development of full-form soft linkages between the models EMEC (Environmental Medium Term Economic Model - a TD CGE model) and TIMES-Sweden (a BU energy system model). A robust and transparent method to translate simulation results between the two models is developed, resulting in intermediate 'translation models' between EMEC and TIMES-Sweden. EMEC provides demand input to TIMES, while TIMES provides feedback on the energy efficiency parameters, the energy mix, and the prices of electricity and heat. These 'translations' can also be used stand-alone to feed into other energy system models. The presented soft-linking process demonstrates the importance of linking an energy system model with a macroeconomic model when studying energy and climate policy. With the same exogenous parameters, the soft-linking between the models results in a new picture of the economy and the energy system in 2035 compared with the corresponding model results in the absence of soft-linking.

EMEC is a static computable general equilibrium model of the Swedish economy developed and maintained by the National Institute of Economic Research (NIER) for analysis of the interaction between the economy and the environment (Östblom and Berg, 2006). The EMEC model includes 26 industries and 33 composite commodities including seven energy commodities. There is also a public sector producing a single commodity. Produced goods and services are exported and used together with imports to create composite commodities for domestic use. Composite commodities are used as inputs by industries and for capital formation. In addition, households consume composite commodities and there are 26 consumer commodities. Production requires primary factors (i.e. two kinds of labour and capital) as well as inputs of materials, transports and energy. Households maximise utility subject to an income restriction, firms maximise profit subject to resource restrictions, the provision of public services is subject to a budget constraint, and the foreign sector's import and export activities are governed by an exogenously given trade balance. The model differs from many other CGE models by having a detailed description of the energy use, environmental economic instruments as well as emissions.

The main structure of TIMES-Sweden was designed within the NEEDS and RES2020 projects, and has since been further developed (e.g. Krook Riekkola et al., 2011; Krook Riekkola et al., 2013). TIMES-Sweden covers the Swedish energy system divided into six main sectors (Electricity and heat, industry, agriculture, commercial, residential and transport), based on the structure of EUROSTAT database. Each sector includes 60 different demand segments that drive the model. The structure and many of the assumptions are similar to the JRC-EU-TIMES model, documented in (Simoes et al., 2013)

Even though the two models have different scientific bases, they both assume cost-minimising behaviour by producers and household demands based on optimising behaviour.

5.5.1 *METHODS*

The recognition that different sets of connection points are needed, depending on which direction the information is being transferred during the iteration process, resulted in two different approaches in mapping of the connection points – one when transferring information from EMEC to TIMES-Sweden and another when transferring information in the opposite direction.

Energy system models are not well suited to address changes in demand due to economic growth. Thus the EMEC model will be the provider of demand drivers from which the demand for goods and services to TIMES-Sweden is estimated. This approach will not differ from running TIMES-Sweden stand-alone, when the demand drivers always are based on results from CGE models like EMEC, the difference will be that they are re-estimated for each iteration-run. All demand segments cannot be treated in the same way and there are cases where no relationship exists between change in demand of a certain commodity and economic growth. Different approaches for translating the output from EMEC into usable input into TIMES-Sweden include: a direct approach based on economic development in a corresponding sector, an indirect approach based on an alternative activity economic development in one or several corresponding sectors, or an assumption of no connections.

Due to their broader focus, CGE models such as EMEC, are unable to explicitly address aspects of the energy system related to i) changes in energy intensity due to introduction of new technologies, ii) changes in the energy mix following changes in energy demand and, iii) changes in electricity and heating prices due to competition of limited energy commodities between and within sectors. These aspects are the focus of the energy system output. To facilitate the transformation of results between TIMES and EMEC, the production function in the soft linked version of EMEC has been changed so that the elasticity between the different energy products in each sector is set to zero, i.e. the energy branch is assumed to be represented by a so-called Leontief structure with fixed input coefficients.

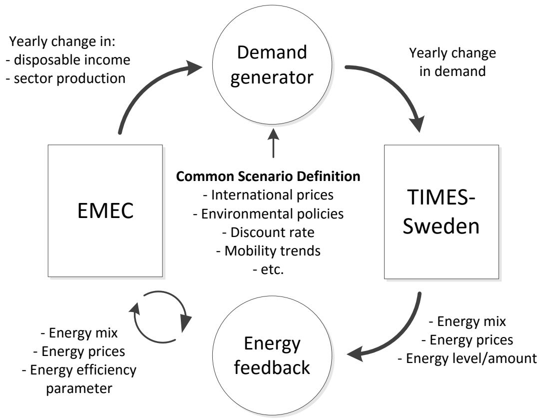


Figure 5.3 Soft-linking between EMEC and TIMES-Sweden.

5.5.2 *RESULTS*

In EMEC, the reference scenario describes a possible outcome for the Swedish economy and energy demand in the long run. The reference scenario is based on the official macroeconomic forecast of NIER with the exception of energy efficiency parameters, which are determined by soft-linking the two models. In the climate scenario, the CO_2 tax is assumed to increase by 50% and the CO_2 prices within the EU-ETS is increased from 16 to 30 €/tonne in 2020 and stays at this level to the end of the modelling period in 2035.

The iteration process (Figure 5.4) starts with EMEC, whereby its macroeconomic outputs are fed into the translation model, providing a set of energy service demands for TIMES-Sweden. The models adapt to each other primarily in the first reference iteration R-2, and there-after only minor changes are made, while the models are considered converged within tolerance.

The lower demand in energy-intensive industries, after the reference iteration process, can be explained by a higher electricity price from TIMES-Sweden when compared to EMEC in isolation. TIMES-Sweden assumes fewer technology options in energy intensive industries to reduce their demand compared with EMEC, which assumes changes in energy demand based on substitution elasticities. Higher electricity prices and lower substitution possibilities imply increased production costs and a decreased demand for energy-intensive goods as their relative price increases.

Soft-linking reinforces the trend towards higher increased demand for transport and services.

The climate scenario is analysed based on three different starting points: a non-linked reference scenario (Climate NL-ref), a non-linked climate scenario (Climate NL-Climate) and a soft-linked scenario (C-x Iteration). In the latter case, when the soft linked reference scenario is the starting point of the climate scenario iterations, the number of iterations does not affect the production level from EMEC to any greater extent. Hence, the differences between C-1 and C-3 are small compared with the differences between R-1 and R-2. The results of the EMEC model have already adjusted to mimic TIMES-Sweden's behaviour in the reference scenario. One reason is that the Swedish power system is almost carbon free, which in combination with the green electricity certificate scheme only gives marginal changes in the electricity price when the EU-ETS price is increased.

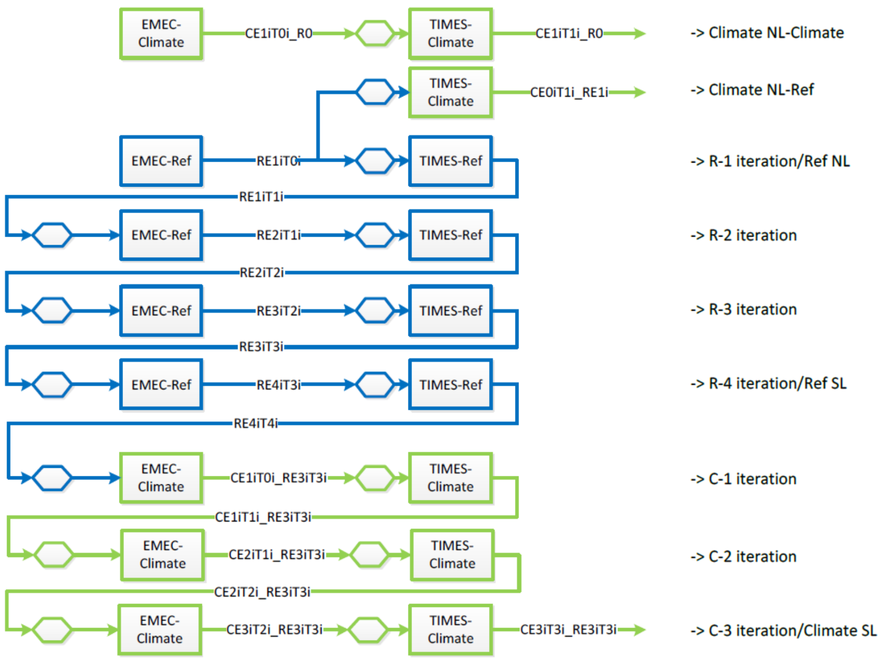


Figure 5.4 The iteration scheme between EMEC and TIMES-Sweden

In order to test if the changes in the results from introducing the soft-linking process had a policy impact, the resulting CO_2 trajectories from TIMES-Sweden were scrutinized. The results show the CO_2 emissions are significantly reduced with soft-linking. This is mainly a result of lower demand for energy services.

5.5.3 *Discussion*

Both EMEC and TIMES are based on national statistics which has permitted the build-up of detailed models. However, the two models are based on two different statistical databases (national accounts versus energy statistics). The national accounts are structured to capture the main economic activities and thereby facilitate a robust analysis of the economy, while the energy statistics are structured in order capture the energy flows and thereby facilitate a robust energy analysis. When identifying connections points, several overlaps and mismatches were identified. Thus, instead of using common measuring points, we identify direction-specific ‘connection points’ to describe the interaction of model results from one model to the assumptions used in the other model.

The biggest challenge and uncertainty in soft-linking iteration is the price information from TIMES-Sweden to EMEC. The prices change between the base year in 2008 and the horizon end year 2035 were found to be exaggerated. The main explanation for this is that the calculated prices in the first modelling years do not include all costs. The optimization solves for the lowest total cost, but when the base years are fixed there is no need to include those cost figures when TIMES-Sweden is used stand-alone and comparing the results from different scenarios in a specific year. In contrast, the soft-linking process compares the price difference between two years with one scenario. This particular issue needs to be solved in future studies.

Changes in investment flows, due to large structural changes in the energy system were aspects that could not be captured in a satisfactory way in this soft-linking methodology. In a major restructuring of the economy, for example caused by the radical reduction of fossil fuel use, investment flows would most likely change substantially and affect the overall investment requirements and in turn give rise to significant general (dis)equilibrium effects.

5.6 South-African Electricity Sector - SATIM-el and SAGE

South Africa has a carbon-intensive economy. The energy sector is responsible for most of the country’s emissions, with 78.9% of total emissions from energy. These emissions have resulted from the extensive use of coal in the generation of electricity, the conversion of coal into liquid fuels, and coal for thermal uses in industry.

The Long Term Mitigation Scenarios (LTMS) study found carbon taxes to have the biggest emissions reduction potential compared to various other mitigation options (Winkler, 2007). In a developing country like South Africa, it is important that policies and measures aimed at achieving the country's emissions reduction targets are not applied to the detriment of other national development objectives. The hybrid model linking the South African TIMES model (SATIM) to the extended South African General equilibrium model of the economy (e-SAGE) addresses this issue.

SATIM is an inter-temporal bottom-up optimisation energy model of South Africa built around the MARKAL-TIMES platform. SATIM uses linear or mixed integer programming to solve the least-cost planning problem of meeting projected future energy demand, given assumptions about the retirement schedule of existing infrastructure, future fuel costs, future technology costs, and constraints such as the availability of resources.

The e-SAGE model simulates the functioning of the economy and uses South Africa's 2007 Social Accounting Matrix (SAM) as data input, accounting for industries and commodities in South Africa, as well as factor markets, enterprises, households and the 'rest of the world'. The 2007 SAM has 61 industries and 49 commodities. It also has 9 factors of production, namely, land, 4 education- based labour groups, and capital which is divided into 1 energy and 3 non-energy capital groups.

5.6.1 Methods

Alternate runs of SATIM and e-SAGE are performed from 2006 to 2040, each time exchanging information about fuel prices, demand, investment (capital growth), electricity production by technology group, and electricity price. Given an initial demand, TIMES computes an investment plan, and a resulting electricity price projection, which is passed onto e-SAGE to see the impact, if any, that this new price projection has on the demand, which then go back to TIMES in the next iteration. The problem is that if both the price and capital growth are imposed onto e-SAGE for the entire model horizon, there is little room for demand to react. Demand tracks the investment (capital growth), which defeats one of the main points of using a CGE.

To circumvent this, only the price projection is imposed onto e-SAGE for the entire model horizon, and the production schedule and capital growth is only gradually imposed. The result of this is that, by the end of the planning horizon, a demand projection has been used that is consistent with price, and can react to price changes. Based on this consistency, the economic impacts of the investment decisions that were made in the power sector can be analysed subject to constraints defined in that sector, such as a nuclear programme or a renewables programme, or how the energy and economy would respond to CO_2 mitigation policies.

The following scenarios are run as a demonstration of the linked models for the purpose of evaluating mitigation actions:

1. A set of TIMES runs without the CGE model, but assuming the same demand as the Reference linked model run for all scenarios:

a. A Reference case of the power sector without any mitigations actions (Reference).

b. A CO_2 tax runs starting at \$5 (R48)/ ton CO_2) in 2016, increasing to \$12(R120)/ton CO_2 in 2025, approximating Treasury's proposed carbon tax.

c. Two renewable energy scenarios:
    - 20% share of centralised generation by 2030 and 30% in 2040 (RE Prog 1); and
    - 30% share of centralised generation by 2030 and 40% in 2040[10] (RE Prog 2).

2. The same set of runs as above but this time with the linked CGE and TIMES models.

[10] RE includes: centralised solar PV, solar thermal, wind, domestic and imported hydro, and biomass.

5.6.2 Results

Total capacity of the TIMES reference case reaches 103 GW in 2040, still dominated by coal with 55GW (54%). Coal also dominates production, maintaining the current share of around 81% through to 2040. Gas (open cycle gas turbines and combined cycle gas turbines) capacity reaches 23GW (23%) for peaking and mid-merit loads. The remainder is made up of solar PV (13%), hydro and pump storage (4%) and nuclear and imports (6%).

The currently proposed CO_2 tax level has a small impact on the system in this scenario. Total capacity is slightly higher at 106 GW in 2040, due to increased share of gas and solar PV that run at a lower capacity factor than coal. The coal share of capacity drops to 51% and production to 79%, whereas gas remains at around 23% of total capacity. The coal production is mainly replaced by solar PV, increasing its share of production from 6% to 7%.

To reach a share of production of 30% in 2040 in program 1 and 40% in program 2, the RE share of capacity reaches 43% and 50% by 2040. The high share of low-capacity technologies means that total capacity goes up to 120 GW and 126 GW, respectively. The RE program pushes the coal share of capacity further down to 30%, and 19% for the two programs, respectively. The gas share of capacity reaches 18% and 23%.

The CO_2 emissions from the power sector of the reference scenario grow to almost double the 2010 levels reaching 430 Mton/annum in 2040. In the CO_2 tax scenario, the annual CO_2 drops by only 3% relative to reference case. However, when using the more optimistic RE costs, a 20% reduction is observed. When the penetration of low emission technologies is imposed directly with the RE programs, the CO_2 emissions drop more radically by 33% and 50%, respectively by 2040.

Comparing the TIMES runs and the CGE-linked runs for the reference case and the CO_2 tax case, the reference cases are identical, given that they have the same demand, and fuel prices. In the CO_2 tax scenario though, there is a drop of the peak demand in the CGE-linked run, showing some demand response from the CGE to the higher electricity price.

All the policy scenarios result in slight GDP loss in 2040 relative to the reference case. In all the policy scenarios, the mining and metals sectors are the most negatively affected, mainly because of the electricity price increase, and the switch away from coal for some of the electricity production. The electricity sector grows quite significantly relative to the base with more investment taking place in this sector, although not enough to avoid a net negative impact on GDP.

5.6.3 Discussion

The results so far indicate that the linked SATIM e-SAGE model is able to contribute to the goal of analysing the trade-off between mitigation and development objectives for South Africa. However, to gain further confidence in the results, more work is still needed in aligning both models, by ensuring consistency between other energy consuming sectors, not only in terms of their energy consumption, but also in terms of how the capital and labour costs computed in e-SAGE affect energy sector decisions in SATIM.

5.7 Danish - IntERACT

As a part of the Energy Agreement from 2012 all parties in the Danish Parliament except one agreed on an ambitious plan for phasing out fossil fuels for energy in Denmark. In 2035 the power and heating sector has to be without fossil fuels and all of the Danish energy system has to be independent of fossil fuels by 2050. As a part of the agreement and to support future planning, a new energy policy analysis model has to be developed.

The model outlined here is decided to be a combination of a CGE model for the Danish economy (CGE-IntERACT) linked with a TIMES model of the Danish energy system (IntERACT-TIMES-DK). The CGE and the TIMES model are being developed simultaneously to secure optimal structural fit and data harmonisation in the linking between the models. A soft-linking approach is chosen and energy demand in the form of services are sent from the CGE to TIMES and fuel mix, energy use, energy cost and energy service prices are returned to the CGE.

The IntERACT project is developing a novel CGE approach by modelling the energy service demand within its economic CGE model, rather than the typical approach of modelling specific energy goods such as oil, gas, coal or electricity. As has already been indicated in section 5.5.3, the traditional approach is not well suited when analysing large scale technological changes such as in the case of a complete green transition and phase out of fossil fuels. The demands for comfortable room temperature, lighting, transport services and process energy are the basic needs of the economy, and it is the impact of the relative costs of these services that have significant influence on the economic behaviour.

The premise in the IntEREACT model is that agents make economic decisions based on the relative prices of energy services, while the specific fuel use and the specific technology applied in order to obtain the energy service is secondary; i.e. economic utility or revenue is not derived from the amount of energy (PJ) of fuel consumed, but rather from the energy services the fuel actually delivers. This leads on from the concept of exergy and useful work as a productive element in the economy, as opposed to gross energy consumption. Agents maximise profit and utility using the costs of the energy service, using relative prices as usual. By using energy services in this method, the economic TD model creates an abstraction of energy and in a sense reduces the role of exact technologies. Indeed the TD model does not make any technological decisions to obtain a given amount of energy services. From the consumers perspective it does not matter how the room is heated (with an explicit technology choice), but rather how much the costs relative to inputs in the production or goods in the utility bundle vary.

5.8 NORWAY - REGIONAL EFFECTS OF ENERGY POLICY (REGPOL)

The goal of the RegPol[11] project is to develop a hybrid energy-economy framework for Norway with special attention to the regional level, combining the

[11] The RegPol project is financed by the Norwegian Research Council. Collaborative research partners are SINTEF Technology and society, NTNU and IFE

technology- rich bottom-up TIMES model with a top-down multi-sector economic computable general equilibrium (CGE) model. CGE-models focus on the interaction between different supply and demand sectors, and are developed to study effects of different policy proposals that apply different instruments within and across the sectors of an economy. CGE-models usually do not include much technical detail, and have little information on the underlying infrastructure.

The majority of research has addressed the national and international level. The RegPol project focuses on the need to better understand how energy policies affect local decisions and how local advantages can be used actively in regional policy addressing implications for the energy sector. Both models will have a subnational geographical level with multiple regions. The TIMES model will have a geographical representation of the energy system, while the CGE model will describe the regional multi-sector economies plus trade and transport between regions. These models are called spatial CGE models (SCGE) and include modelling elements from new economic geography.

A regional model framework is needed to assess the effect of technology drivers on the deployment of technologies, localisation of new large scale production and changes in end use. Parameters, such as energy demand, population density, local electricity production, untapped resources, available energy infrastructure and geographical conditions influence the future regional development.

The model structures will be general, but a relevant geographical division for analysing energy policies consists of the Norwegian electricity price areas. Some areas have significant power surpluses while others have significant power deficits. Together with transmission constraints, this is relevant for location of both new production and new consumption. Some relevant analysis cases are:

- In Norway there is a political objective to build a substantial amount of renewable energy supported by green electricity certificates. Norway has excellent wind resources, and the RegPol project will analyse which project locations are advantageous, and how projects will affect regional development.

- The electrification of offshore oil and gas fields in order to avoid greenhouse gas emissions would constitute major electricity consumers. Such projects have created strained power situations, and should be analysed within a regional hybrid modelling framework such as RegPol.
- There has been increased focus on Norway's potential to store water in reservoirs. Norwegian hydropower could play a balancing role as a green battery within a European power system with a high share of power production from intermittent sources as wind and sun. This will require new production capacity and new interconnections to be built, both internally to access export links, and to the export markets.
- Development of the grid infrastructure is in itself an important question to analyse. Low transmission capacities may induce different price-levels between price areas, with corresponding consequences for regional industries and other demand.

The hybrid framework with TIMES and the SCGE model will be designed for efficient successive exchanges of adjusted solutions. Different designs for linking the models are investigated, both soft-linking, hard-linking and full integration. The higher data granularity, the more important it becomes to handle data exchange with automatic routines. RegPol starts with a soft-linking approach, but seeks to automate the linking and embed it in the hybrid framework.

Since production and consumption takes place in different locations, the spatial characteristics are important in order to find optimal solutions and effective policies. Various policies (like energy taxes and subsidies) also have regional rates and different regional impacts. The combination of technological and economical models with regional resolution is well suited to improve current analyses and provide the best guidance for future sustainable solutions.

5.9 CRITICAL MESSAGES FROM APPLIED HYBRID METHODS

There are many useful points to note in this state of the art review of ETSAP hybrid energy-economy modelling. A final synthesis of the critical messages from all of the model applications and discussions are summarised below.

A restructured low carbon world economy is imperative to mitigate climate change. Modelling results repeatedly show CO_2 emissions are significantly lower in hybrid models as a result of demand adjustments. The range of the differences between isolated energy system CO_2 emissions and their comparable hybrid model is between -5 and -13% by 2050, depending on the carbon intensity of the economy in the region in question..

Economic impacts vary regionally, again dependent upon the energy intensity of a nation's economy, the trade partnerships, competitiveness and level of development. Loss of GDP can be as high as 5%/yr by 2050 in developing countries, while up to 3%/yr by 2050 in developed countries depending on the implemented mitigation mechanisms and revenue recycling schemes. Short term economic gains are to be made in energy efficiency measures.

Both energy system models and CGE models play an important role in the existing energy and climate policy analyses. Even when running the two kinds of models stand-alone, the models use assumptions which are based on results from the other model (directly and indirectly). Thus, by soft-linking energy system models and CGE models the energy and climate policy analysis becomes more transparent.

Hybrid Models have already played a critical role in carbon mitigation policy and should continue to play a key role in policy advice in upcoming COP talks. Hybrid energy-economy modelling has an increasingly key role to play in accurately modelling the economic impact of climate mitigation, while addressing the most cost-effective technological solutions.

Furthermore, hybrid linking displays non-linear, sectoral non-uniform demand responses that cannot be captured with demand price elasticities, increasing the understanding and transparency of the model results. Model methodological and documentation transparency is a critical factor in moving beyond publishing and presenting papers. Replicability is nearly impossible and makes difficult the traditional scientific process. A move to more open models is required for more rigorous validation of models and model results.

A challenge and source of uncertainty in soft-linking hybrid models is the price information from bottom up optimisation models to top down models. The price change between the base year and the end of horizon year are found to be exaggerated. The main explanation for this is that the calculated prices in the first modelling years do not include all costs. The optimization solves for the lowest total cost, but when the base years are fixed there is no need to include those cost figures. In contrast, the soft-linking process compares the price difference between two years with one scenario. This particular issue need to be solved in future studies.

Changes in investment flows, due to large structural changes in the energy system, are difficult to satisfactorily capture in typical soft-linking methodologies. A major restructuring of the economy as a result of a radical reduction of fossil fuel use would most likely change investment flows substantially and affect the overall investment requirements. In turn this would give rise to significant general (dis)equilibrium effects resulting in model uncertainty.

5.10 Acknowledgements

The authors wish to acknowledge journals of Climate Policy, Energy, Energy Economics and Energy Policy where relevant original research papers have been published (Fortes et al., 2014, 2013; Strachan et al., 2009; Strachan and Kannan, 2008).

Chapter 6 The macroeconomic impacts of a decarbonised energy system in Ireland - Hybrid energy-economy modelling using Irish TIMES MACRO

Primary Outputs:

Glynn, J., Gargiulo, M., Chiodi, A., Deane, P., Ó Gallachóir, B., 2015. Macroeconomic impacts of equitable carbon budgets for decarbonising the Irish integrated energy system. Energy Policy (submitted).

Gargiulo M, Glynn J. and Ó Gallachóir B. 2014 Modelling macroeconomic impacts of a carbon constrained energy system using Irish-TIMES MSA Proc International Association of Energy Economists 2014 Conference October 28 – 31, 2014 Rome, Italy.

Glynn, J., Gargiulo, M., Ó Gallachóir, B., 2014. Modelling the macroeconomic impacts of decarbonising the irish energy system using Irish-TIMES MSA. Presented at the Irish Society for New Economists, 4th September 2014, National University of Ireland, Galway, Ireland.

Glynn J., Chiodi A., Gargiulo M., Deane P., Ó Gallachóir B. Optimum Irish energy system in an oil constrained future. In proceedings of: 12th IAEE European Energy Conference, Energy Challenge and Environmental Sustainability, 9-12 September 2012, Venice, Italy.

6.1 Introduction

The evidence is now unequivocal; global anthropogenic emissions are leading to an average warming of the climate (Pachauri et al., 2015). Global mean surface temperature is projected to increase by 3.7°C to 4.8°C during the 21st century without additional mitigation (Edenhofer et al., 2014). The European Union is committed to policies to mitigate the risks of catastrophic climate change and to minimise the eventual adaptation required of EU citizens. The long term policy perspective is that EU GHG emissions reductions should be between 80% - 95% by 2050. In the short term the EU 2020 Climate and Energy Package sets a target reduction of 20% in GHG emission by 2020 relative to 1990 levels. Directive 2009/29/EC sets an emission trading scheme (ETS) target of a 21% reduction below 2005 levels by 2020, while the effort sharing Decision 406/2009/EC sets a non-ETS target for the EU of 10% reduction on 2005 levels by 2020 for the remaining sectors in the economy (EU, 2009a, 2009b). The Irish portion of this decision amounts to a 20% non-ETS emissions reduction target on 2005 levels by 2020. Ireland is actively pursuing these policies (White, 2015) while also engaged in action plans for energy efficiency (NEEAP) and increasing renewable energy (NREAP) penetration (EU, 2009c, 2006). Ireland's target is 16% gross final consumption from renewables in 2020. Although Ireland has had success in increasing penetration of renewable electricity (RES-E) and is aiming for a 40% contribution, notably via wind power, yet when refocussing on the overall renewable energy targets Ireland is only half way to target, with considerable work required to meet the renewable heat (RES-H) target (12%) and renewable transport (RES-T) target (10%) (Howley et al., 2014; Pye et al., 2014). Ireland may comply with 2020 emissions reduction targets using banked emissions from the years of economic austerity spanning the global economic crisis, but is unlikely to meet emissions reduction targets without additional policy measures beyond 2020 to 2035 (EPA, 2015).

6.1.1 *Motivation and paper outline*

Irish climate and energy policy has been informed by the Irish-TIMES energy systems model previously (Deane et al., 2013), investigating medium term targets to 2020 (Chiodi et al., 2013a), long term targets to 2050 (Chiodi et al., 2013b), questions of bioenergy import dependency (Chiodi et al., 2015a), technical realism of the electricity sector soft-linked to power systems model (Deane et al., 2012), energy security of supply (Glynn et al., 2014), and agriculture sector feedback to energy system emissions targets (Chiodi et al., 2015b). These previous studies outline the energy system evolution under differing technical or environmental scenario constraints and solve a partial equilibrium least cost optimisation, i.e. without demand response to prices. Additionally this paper outlines how the overall economy may react to a decarbonising energy system in a general equilibrium with feedback between the energy system and the macro-economy. The induced changes in economic growth, sectoral energy service demands, consumption and investments are brought about by substitution of investment capital and human capital with productive energy uses. The method outlined in this paper is the first use of a decomposition general equilibrium method to calculate first order costs of decarbonising the energy system to the Irish economy. The paper estimates GDP losses, changes in consumption and investment for three scenarios, one in which there is an 80% reduction in energy system GHG emissions by 2050, and the second and third scenario whereby an equitable cumulative emissions budget of 614MtCO_2, or 340MtCO_2, constrain the energy system between 2020 and 2070.

6.2 Methodology

6.2.1 *Modelling approach using the Irish TIMES model*

The Irish TIMES model is built with The Integrated Markal-Efom System (TIMES) framework, written in the General Algebraic Modelling Software (GAMS) and solved with CPLEX. The framework is developed within an implementing agreement of the International Energy Agency (IEA); the Energy Technology Systems Analysis

Programme (ETSAP), is distributed freely, well documented, transparent, maintained, and upgraded on an ongoing collaborative basis.

TIMES is a techno-economic bottom-up (BU) model generator for local, national, or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy system, but may also be applied to detailed studies of individual sectors (e.g. the electricity sector or transport sector). TIMES computes a time varying inter-temporal partial equilibrium on inter-regional energy markets. The objective function maximizes total surplus. This is equivalent to minimizing the discounted total energy system cost while respecting environmental, technical, and policy scenario constraints. The system cost includes investment costs, operation and maintenance costs, cost of imported fuels, less the income from exported fuels, the terminal values, and salvage value of technologies at the end of the horizon. The technical foundations of MARKAL models are outlined in Fishbone and Abilock (Fishbone and Abilock, 1981) while the full updated technical documentation of TIMES is hosted online[12] with the ETSAP group (Loulou et al., 2005).

6.2.2 *Model sets and assumptions*

The Irish TIMES technology database contains descriptive time dependant economic and technical data for approximately 1600 supply and demand side energy technologies. The model specification has 12 annual time slices; four seasons, day, night, and peak for a time horizon of 45 years from the base year of 2005 to 2050. The model is cyclically updated with physical energy service demand projections derived from macroeconomic drivers. The model version used in this analysis is based on macroeconomic forecasts from the Economic and Social Research Institute medium term review in 2013 (FitzGerald et al., 2013). These demand driver projections utilise the ESRI's in house HERMES model in conjunction with the GEM-

[12] http://www.iea-etsap.org/web/Documentation.asp

E3 model of industry Autonomous Energy Efficiency Improvement (AEEI, GEM-E3) (Fitzgerald and Kearney, 2002; Hennessy and FitzGerald, 2011). Primary energy supply commodity prices are based on the 2012 IEA current policy scenario in the world energy outlook (IEA, 2012). Domestic bioenergy potentials and costs are outlined in (Chiodi et al., 2015a) taken from a range of most recent national studies where available. Non-dispatchable renewable electricity generation is limited at 70% per time slice and 50% on annual average based on technical limits (Eirgrid and SONI, 2010; ESB international, 2008). Detailed model assumptions and inputs are available at http://www.ucc.ie/en/energypolicy/ irishtimes/. This model does not include non-energy related agricultural emissions, as such emissions reduction targets are adjusted exogenously assuming agricultural GHG emissions maintain the same growth rate as national projections to 2020 and onwards to 2050 (EPA, 2013).

6.2.3 Modelling approach using Macro Stand Alone

MACRO Stand Alone (MSA) as outlined in the previous chapter ((Glynn et al., 2015a) section 5.3) enables a hard-linked hybrid approach to calculate a general equilibrium solution between energy service demands and the energy system costs in the Irish TIMES MACRO framework (See Figure 6.1). The original MACRO framework produced models that were of such a large size that it presented computing difficulties with modern desktop-computers, as well as time constraints, and often calibration was a struggle to gain a sufficiently stable non-Linear (NL) solution (Manne and Wene, 1992). The method used here, an updated approach to MACRO, called MACRO Stand Alone (MSA), decomposes TIMES-MACRO (TM) into a small NL macroeconomic model, where the TIMES energy system is substituted by quadratic cost-supply functions (QSF) for each energy service demand (Kypreos and Lehtila, 2015). This enables the optimisation of the overall objective function for welfare maximisation, giving a general equilibrium between prices and demands, all within a reasonable computational time frame (<5min for a single region model), 100 times faster than the original MACRO algorithm.

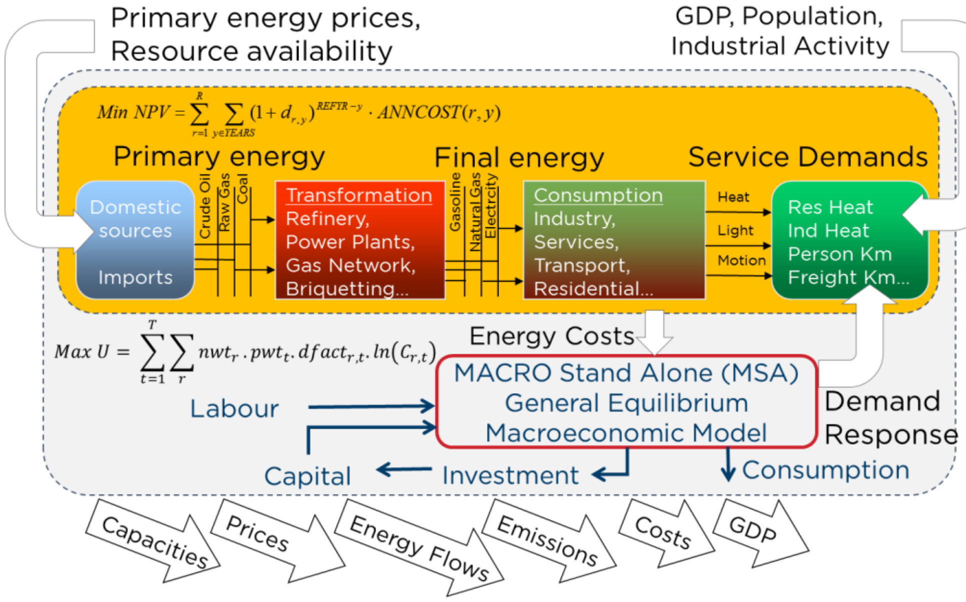


Figure 6.1 Simplified schematic of the Irish-TIMES MSA model & data flow

MACRO solves an objective function which maximises an intertemporal utility function for a single representative producer-consumer agent (Equation (1)). The key variables and equations outlined below are the capital stock (K), labour (l), energy services (DEM), and the elasticity of substitution (ρ), as the factors of production determine the output (Y) of the economy (2). Simultaneously, Production (Y) balances with regional Consumption (C), Investment (INV), and the Energy system Costs (EC) equation (3). In a single region application such as this case, the production function is not weighted by the wealth distributing Negishi weights, nor is net export trade in non-energy related numeraire good (NTX(nmr)) required to be modelled. Therefore this model does not take into account international competitiveness issues that would result from differing rates of decarbonisation within trade partners, differing cost of carbon, and their resulting differing production costs.

$$Max\ U = \sum_{t=1}^{T} \sum_{r} nwt_r \,.\, pwt_t . dfact_{r,t} . ln\left(C_{r,t}\right) (1)$$

$$Y_{r,t} = \left(akl_r \cdot K_{r,t}^{kpvs_r \cdot \rho_r} \cdot l_{r,t}^{(1-kpvs_r)\rho_r} + \sum_k b_{r,k} \cdot DEM_{r,t,k}^{\rho_r}\right)^{\frac{1}{\rho_r}} (2)$$

$$Y_{r,t} = C_{r,t} + INV_{r,t} + EC_{r,t} + NTX(nmr)_{r,t} (3)$$

nwt – Negishi Weights

pwt – Weight Multiplier

dfact – Utility discount factor

C - Consumption

Y – Production

INV – Investment

EC – Energy Cost

NTX – Net exports of Numeraire good

akl – Production function constant

K – Capital

kpvs – Capital value share

l - Labour annual growth

b – Demand coefficient

ρ – Elasticity of substitution

DEM - Energy Demands

k - Technology type subscript

r - Region subscript

t - Time subscript

The calibration routine (CSA) is used to calculate demand decoupling factors and to ensure that the baseline energy service demands and macroeconomic projections are replicated with the MSA routine. Only once the CSA routine has converged with acceptable tolerance can policy scenarios be assessed with the full MSA routine.

The labour-capital aggregate and demand multiplier coefficients akl, and b, are benchmarked in the constant elasticity of substitution (CES) production function (equation 2) allowing a relationship between economic activity, price of energy services, and demand for energy services to be formulated. However, this formulation cannot take into account price independent technological change, as a result of the constant elasticity of substitution. The demand decoupling factors (ddf) for each energy service demand enable the production function to take account of price independent structural changes in the economy, primarily increased energy efficiency and increased productivity as a result of technology progress.

Once calibrated, MACRO endogenously calculates energy service demand responses for a policy scenario as a function of economic activity and relative energy prices to the baseline calibration scenario. These factors are in turn calculated as a function of substitution between the factors of production and the energy costs as a result of policy constraints upon the energy system. An iterative process is required to balance the price dependent energy demands from the production function MACRO model with the energy service demands from the energy systems TIMES model. This forms the essence of the macroeconomic feedback between the TIMES model and the MACRO model. The TIMES model provides energy costs to MACRO and MACRO provides energy demands to TIMES, iterating until the energy service demands of both models converge within an acceptable specified tolerance. The algorithm results in an estimate of the macroeconomic impacts of decarbonising the energy system given by GDP change, consumption and investment changes, as well as estimates of price relative energy service demand changes.

6.2.4Scenario definition

The set of scenarios considered are chosen to outline aspects of relative energy system changes under differing climate mitigation policy choices, their implied constraints, and their relative energy service demand responses to macroeconomic feedback. All scenarios have their solution fixed to the reference solution to 2015 and evolve thereafter.

i. BAU - Business as Usual Scenario. The first scenario delivers an energy system which meets energy service demands at least cost, without emissions constraints or energy efficiency improvements. It shows the evolution of energy system with the continuation of current myopic choices.
ii. REF - Reference Energy System Scenario. This scenario shows the least cost optimal energy system evolution in the absence of emissions constraints.
iii. CO2-80. This scenario achieve at least an 80% reduction in CO2 emissions by 2050 in line with the interim targets of EU 2020 climate energy package (EU,

2009a, 2009b). Non-energy agriculture emissions are assumed to grow by 4% over 2005-2020 and remain constant thereafter (EPA, 2013).

iv. CO2-80 MSA. This incremental scenario requires an 80% reduction in CO2 emissions by 2050 while the MACRO module is used to calculate demand responses and macroeconomic impacts.

v. CO2 614Mt. This scenario applies a cumulative CO_2 budget of 614 $MtCO_2$ between 2020 and 2070 without interim emissions pathways targets. This constraint is based on an equitable population weighted budget of future emissions of $1000GtCO_2$, a mid-century global population of approximately 10 Billion, a lifetime budget of 100t CO_2 per person, and an Irish population of 6.14 million.

vi. CO2 614Mt MSA. This incremental scenario applies a cumulative CO_2 budget of 614 $MtCO_2$ between 2020 and 2070 with MACRO module feedback.

vii. CO2 340Mt. This applies a cumulative CO_2 budget of 340 $MtCO_2$ between 2020 and 2070. This constraint is based on population weighted allocation of the global cumulative emissions of 3200 $GtCO_2$ allowed under a 2°C scenario. The Irish cumulative budget of 1.9 $GtCO_2$[13] less past emissions of 1.624 GtCO2 leaves 340 $MtCO_2$ remaining, not considering non-energy agricultural emissions. This scenario attempts to account carbon-debt (Matthews, 2015).

viii. CO2 340Mt MSA - a cumulative CO2 budget of 340 $MtCO_2$ between 2020 – 2070 with MACRO feedback

6.3 Results

Irish CO_2e emissions in the energy system are estimated to rise from 42.2 $MtCO_2e$ in 2015 as Irish Economic activity returns to growth thereafter. This excludes exogenous agriculture non-energy emissions of 18.8 $MtCO_2e$ in 2015, giving total emissions in 2015 of 61 $MtCO_2e$ (See Figure 6.2). Under the business as usual scenario

[13] Data Sources: Global Carbon Project - http://www.globalcarbonproject.org/carbonbudget/14/data.htm
Carbon Dioxide Information Analysis Center - http://cdiac.ornl.gov/trends/emis/meth_reg.html
United Nations Populations Division - http://esa.un.org/unpd/wpp/

emissions rise sharply to 49.4 $MtCO_2e$ with economic recovery to 2020, and grow to a peak of 52.5 $MtCO_2e$ in 2045. Contrasting with this, the reference scenario shows a flat projection to 42.2 $MtCO_2e$ in 2050. The three largest emitting sectors in the reference scenario in 2050 are Agriculture at 19 $MtCO_2e$, Transport at 14.7 $MtCO_2e$ and electricity generation at 11.2 $MtCO_2e$. The CO2-80 scenarios both follow EU decline rates of 2.2% to 2020 and 1.7% thereafter to final emissions of 6.8 $MtCO_2e$ in 2050, while exogenous agricultural emissions remain at 19 $MtCO_2e$. The cumulative constraint decarbonisation scenarios of 614 $MtCO_2e$ and 340 $MtCO_2e$ show much faster decline rates with interplay with economic feedback enabling some optimisation of discounted welfare, balancing short term emissions, and long term abatement costs. Annual emissions affectively half in the 340 $MtCO_2$ budget scenario to 22.4 $MtCO_2e$ in 2020, and slowing onward to 1.4 $MtCO_2e$ in 2050. The remaining details are visualised in Figure 6.2. The transport sector, and the ETS electricity generation sector, are those that most aggressively require decarbonising, again in the absence of action in the Agriculture sector non-energy related emissions.

The range of marginal abatement costs of CO_2 are essentially logarithmic in scale across the set of scenarios. CO_2 abatement costs in 2020 range from €60/tCO_2 to €560/tCO_2 rising to €446/tCO_2 to €3250/tCO_2 in 2050 in real terms (See Figure 6.3). In the case without price sensitive demand response the CO2 340Mtscenario drives the marginal abatement cost to over €8000/tCO_2 in 2050. Maximising the Irish social good by minimising the carbon intensity of consumption is a potential systematic target to minimise carbon emissions, balanced with sectoral subordinate objectives of maximising the production of low carbon intensity per value added goods and services of individual sectors.

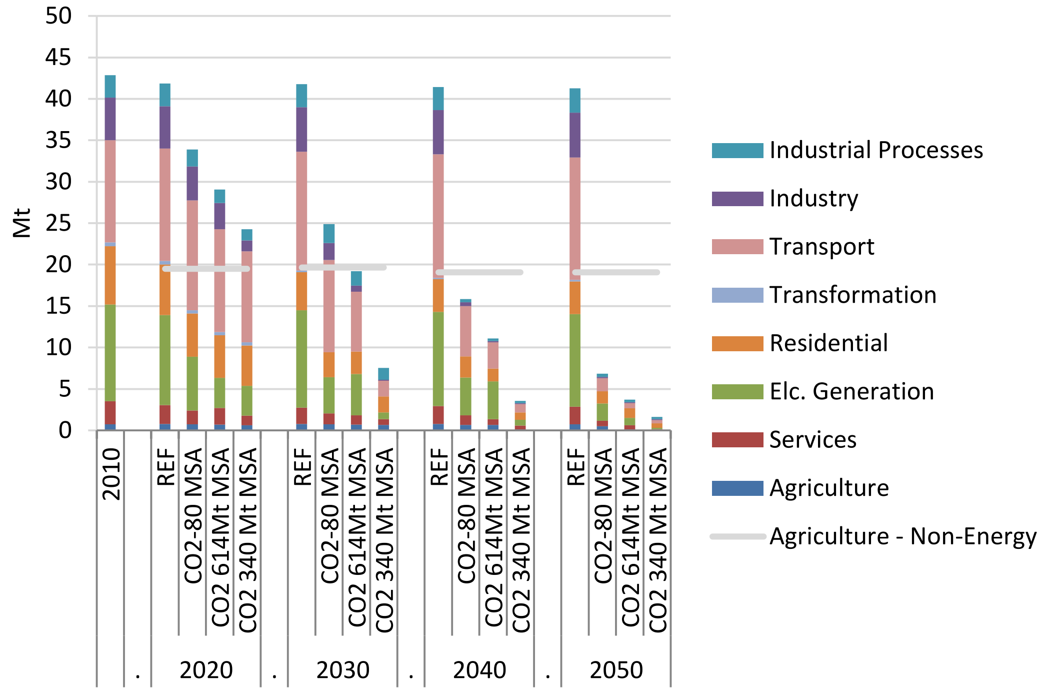


Figure 6.2 Carbon Dioxide Emissions Trajectories per sector for each scenario run.

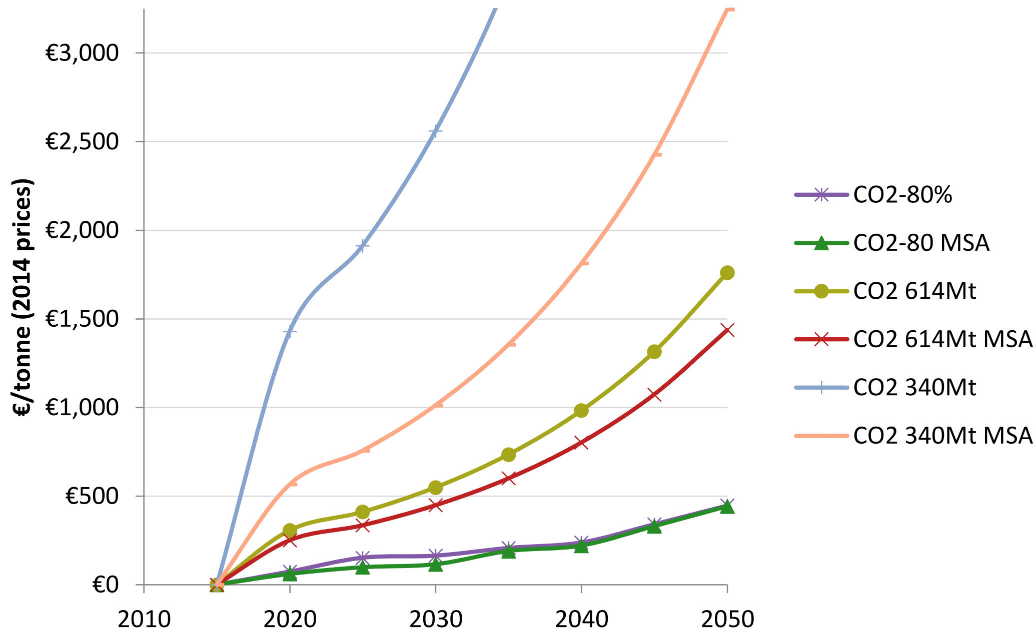


Figure 6.3 Marginal Abatement Price of CO2

6.3.1 *OVERALL ENERGY SYSTEM OUTLOOK*

The overall makeup of the energy system changes radically across the set of scenarios considered. The BAU and REF cases are proportionally a continuation of the current energy system. Oil and Gas dominate the fuel mix at 8.6 Mtoe and 5.4 Mtoe, respectively and account for 82% of the reference primary energy requirement

(TPER). The 2050 Reference energy system shows a 16% reduction in primary energy requirement to 17 Mtoe from 20.2 Mtoe in BAU case.

The decarbonisation scenarios lead to reductions in TPER relative to the REF of between 20% - 14% as a result of energy efficiency, demand reduction, and fuel switching. Natural Gas is used as a bridging fuel in the medium term, being substituted by a trend towards consumption of bioenergy for energy insensitive demands in transport and industry, and electrification in less intensive demands in lighting and heating. This push to electrification increases installed generation capacity from 7.2 GW in the 2050 Reference case, to 17 GW in the 340MtCO_2 MSA case where 12.57 GW of capacity is renewables, and where onshore wind generation accounts for 6.9 GW. Gas-CCS capacity from 1.4 GW to 2.25 GW is required in the decarbonisation scenarios by 2050, alongside biomass generation of up to 2.4GW, and solar generation capacity of up to 2.9GW.

The sectoral proportions of Total Final Energy Consumption (TFC) remain as they are today. The TFC in the reference case in 2050 is 14.2 Mtoe, with the decarbonisation scenarios ranging from 11.3 Mtoe to 11.8 Mtoe. Fossil fuels as a proportion of TFC drop from 76% in the reference case, to 20% in the CO2 340Mt scenario in 2050. Bioenergy represents more than 40% TFC in all decarbonisation scenarios in 2050, with electricity representing the remainder, ranging between 25% - 35% TFC in the decarbonisation scenarios. The shift to indigenous bioenergy and renewables has a positive influence on energy security by reducing import dependency to 69% in the CO2 340Mt scenario, from 91% in the reference scenario in 2050.

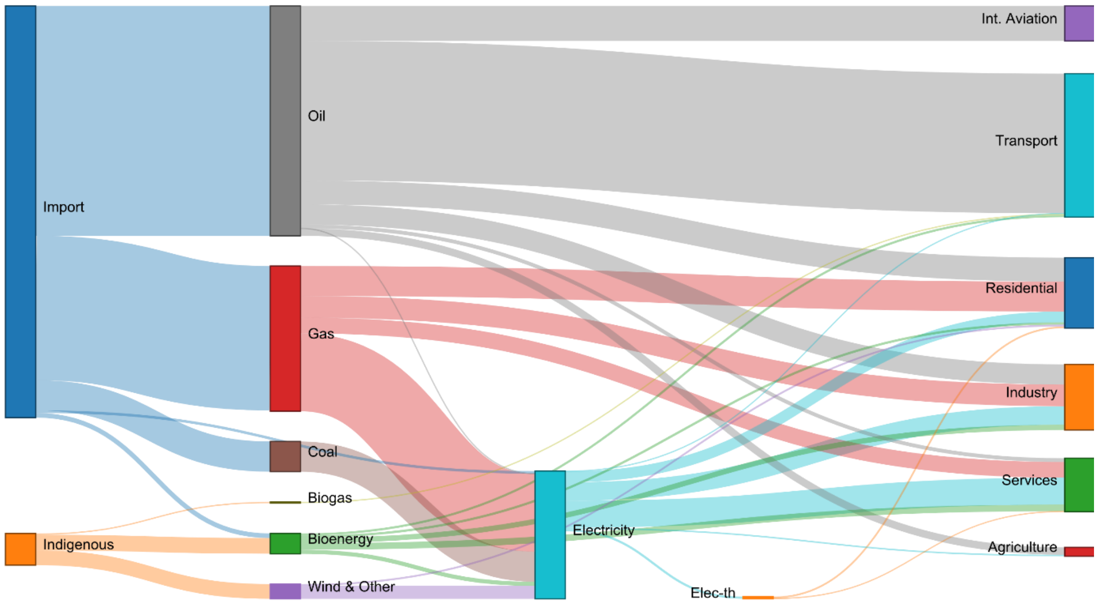


Figure 6.4 Business as Usual (BAU) Irish energy system in 2050

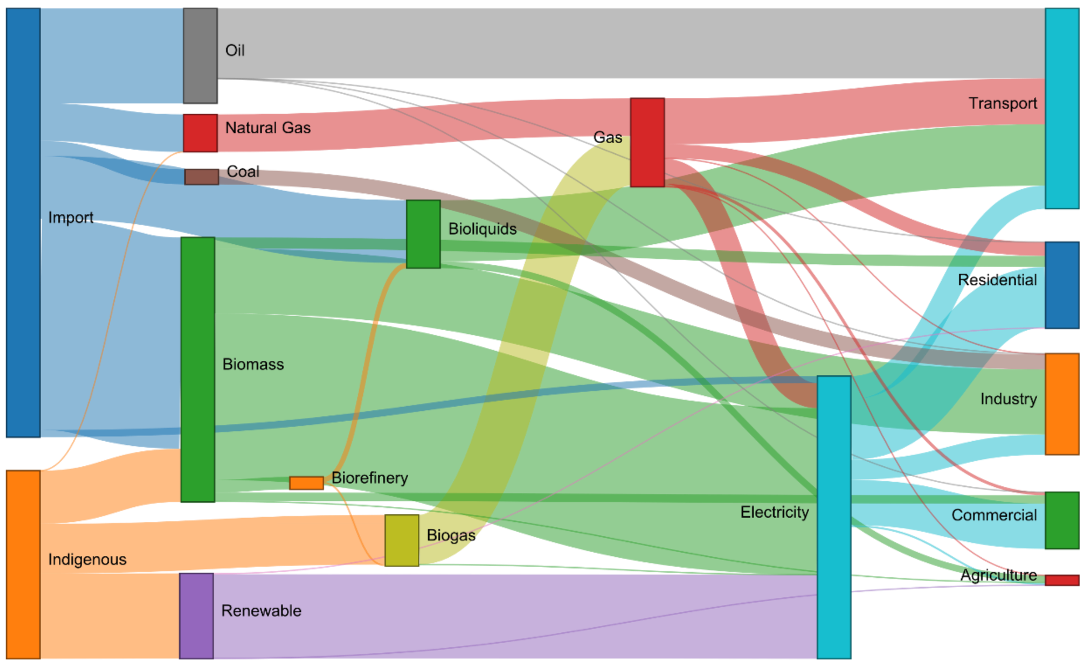


Figure 6.5 The Irish energy system under a 340Mt CO_2 cumulative constraint in 2050.

6.3.2 ENERGY SERVICE DEMAND RESPONSE AND CONSUMPTION

The novel element in this analysis of decarbonising the Irish energy system is the ability of each of the energy service demands to endogenously respond to price. As already seen this model element significantly affects the decarbonisation trajectories and the CO_2 abatement cost. Intuitively, scenarios, sectors, and energy service demands with the largest abatement costs incur the largest energy service demand adjustment. Energy service demand reductions, relative to the reference case in the decarbonisation scenarios, range up to 30% in commercial cooking and residential water heating, and further up to 45% demand reduction in energy insensitive industry producing lime and cement. The abatement cost of CO_2 is exacerbated for energy service demands with limited alternative low carbon technology options (Table 6.1). This shows the need for innovation in construction.

In terms of long distance passenger transport options, private car energy service demand drops by 6% - 8% for the decarbonisation scenarios by 2050, which equates to 3700 to 4800 million passenger-kilometres. Motorcycle demand drops 7%-12%, with intercity diesel trains showing demand reductions of 6% - 14% by 2050, all relative to the reference scenario. Road freight sees a similar reduction in demand of 8% - 12%, or 2500 and 3400 million tonne-kilometres of freight by 2050.

These demand reductions are induced by the cost of the technology choices and fuel switching seen in Figure 6.6, for private, public and freight transport. Conventional hydrocarbons are all but removed in the decarbonisation scenarios transport system by 2050. Private transport is largely electrified with remaining gasoline consumption used in high efficiency hybrid-electric vehicles.

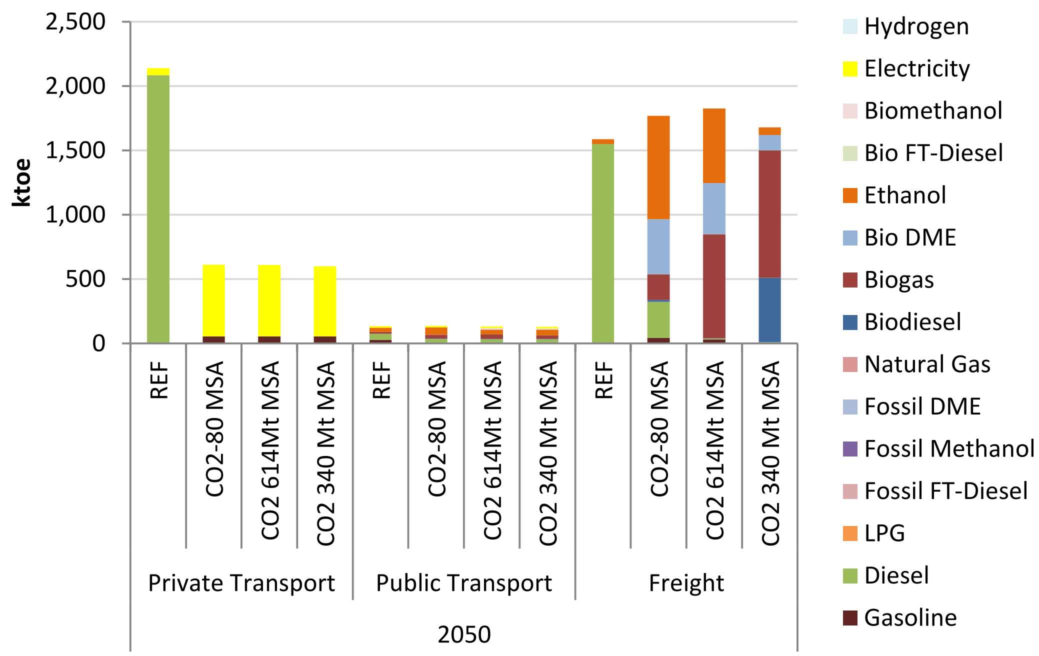


Figure 6.6 Transport final energy consumption by Mode in 2050

Demand Description	Unit	2030				2050			
Transport		**REF**	**CO2-80 MSA**	**CO2 614Mt MSA**	**CO2 340Mt MSA**	**REF**	**CO2-80 MSA**	**CO2 614Mt MSA**	**CO2 340Mt MSA**
Passanger Transport	MPkm	74,971	-3.8%	-5.0%	-6.5%	86,024	-5.4%	-5.7%	-7.5%
Freight Transport	MTkm	25,399	-3.6%	-6.8%	-10.6%	30,123	-8.4%	-9.1%	-11.7%
Int. Shipping	PJ	41	-7.3%	-11.9%	-19.1%	48	-16.0%	-16.4%	-19.2%
Residential									
Hot Water	ktoe	572	-4.4%	-9.3%	-13.5%	649	-8.4%	-9.7%	-11.9%
Refrigeration	ktoe	70	-2.1%	-4.5%	-6.3%	72	-5.5%	-6.2%	-8.9%
Other Electric	ktoe	141	-6.6%	-12.5%	-16.6%	151	-14.3%	-15.7%	-20.9%
Lighting	ktoe	123	-3.9%	-9.0%	-12.8%	131	-10.5%	-10.2%	-14.0%
Space Heating	ktoe	1,446	-3.8%	-8.9%	-12.1%	1,395	-7.8%	-11.8%	-16.0%
Dish Washing	ktoe	25	-2.7%	-5.5%	-7.8%	26	-6.9%	-7.6%	-10.7%
Clothes Washing	ktoe	31	-2.3%	-4.6%	-6.6%	31	-5.8%	-6.4%	-9.1%
Cooking	ktoe	76	-2.8%	-6.2%	-9.0%	78	-7.9%	-9.9%	-15.2%
Clothes Drying	ktoe	25	-2.3%	-4.6%	-6.6%	26	-5.8%	-6.4%	-9.1%
Commercial									
Water Heating	ktoe	184	-8.9%	-14.3%	-19.0%	193	-15.7%	-17.3%	-21.9%
Refrigeration	ktoe	49	-5.2%	-10.1%	-13.7%	54	-12.3%	-13.1%	-17.8%
Public Lighting	ktoe	88	-9.0%	-13.9%	-19.1%	97	-18.6%	-17.5%	-22.5%
Other Electric	ktoe	431	-5.7%	-12.4%	-16.0%	525	-12.9%	-15.5%	-20.8%
Lighting	ktoe	372	-6.6%	-12.6%	-16.6%	447	-14.2%	-15.4%	-20.4%
Space Heating	ktoe	657	-1.7%	-9.9%	-15.4%	691	-8.9%	-15.7%	-23.6%
Cooking	ktoe	108	-7.2%	-13.9%	-20.5%	115	-17.7%	-21.4%	-29.8%
Cooling	ktoe	131	-3.1%	-7.1%	-9.6%	139	-8.0%	-9.6%	-13.5%
Industry									
Cement	Mt	5	-21.7%	-34.1%	-44.8%	6	-18.3%	-22.3%	-26.7%
Lime	Mt	0	-10.7%	-24.5%	-36.8%	0	-25.4%	-41.3%	-53.0%
Other Chemicals	ktoe	318	-8.2%	-11.8%	-14.9%	333	-13.4%	-14.3%	-19.8%
Other Non Ferrous Metals	ktoe	420	-9.7%	-12.1%	-14.2%	440	-12.0%	-12.6%	-18.0%
Other Non Metallic Minerals	ktoe	103	-8.1%	-11.4%	-14.8%	103	-15.9%	-12.7%	-18.8%

Other Non energy intensive	ktoe	764	-8.4%	-11.9%	-15.2%	762	-13.5%	-14.4%	-19.9%

Table 6.1 Energy Service Demand responses per scenario in 2030 and 2050

Alternatively to using macro stand alone to estimate energy service demand response to prices, TIMES can also utilise own-price elasticities for energy service demands to compute a supply-demand equilibrium; these scenario runs are generally referred to as elastic demand (ED) scenarios, in TIMES-ED. The equilibrium is driven by the user-defined specification of demand functions, which determine how each energy service demand varies as a function of the marginal price of that energy service. Comparing the demand price response driven by the quadratic supply function in MSA as opposed to the linear price response of Elastic Demand, shows that the larger the deviation from the calibration base marginal price of demand, the convexity of price response (MSA) or steepness of the price response curve for elastic demand can give rise to discrepancies in demand response between the two methods. Depending upon the level of technology options for a specific energy service demand and where the supply-demand equilibrium lies on both ED and MSA supply curves, the demand response varies between both methods. However, both methods give similar demand responses, and elastic demand option is far simpler and quicker to run.

6.3.3 Economic impacts of mitigation

It is important to remember that TIMES models do not forecast reality, but instead can be viewed as the decision making process of a benevolent system planner, minimising the cost of the energy system in line with the social good. Enforcing a decarbonisation pathway shifts the portfolio of energy system costs toward increased investment in new generation capacity, reducing the fuel bill of incumbent technologies, while minimising other variable costs. Figure 6.7 shows the cost breakdown for the years 2030 and 2050 for the reference scenario and the decarbonisation scenarios as a percentage of adjusted projected GDP. The reference energy system cost is €23bn in 2030, 8.7% of €267bn projected GDP in 2009 euro prices. The gross cost of the CO2-80 scenario and the CO2 614Mt scenario do not increase appreciably in 2030 relative to the reference case, rather there is an increase in investment costs of 11% - 26%, with a reduction in fuel costs of 18% - 29%. The CO2 314Mt scenario increases system costs to €25Bn, or 9.8% of €260Bn adjusted projected GDP. The trend changes somewhat by 2050, with increases in real terms and as a proportion of GDP for the energy system costs. Fuel costs in the 2050 CO2 340Mt case are largely similar to the reference case at €10bn.

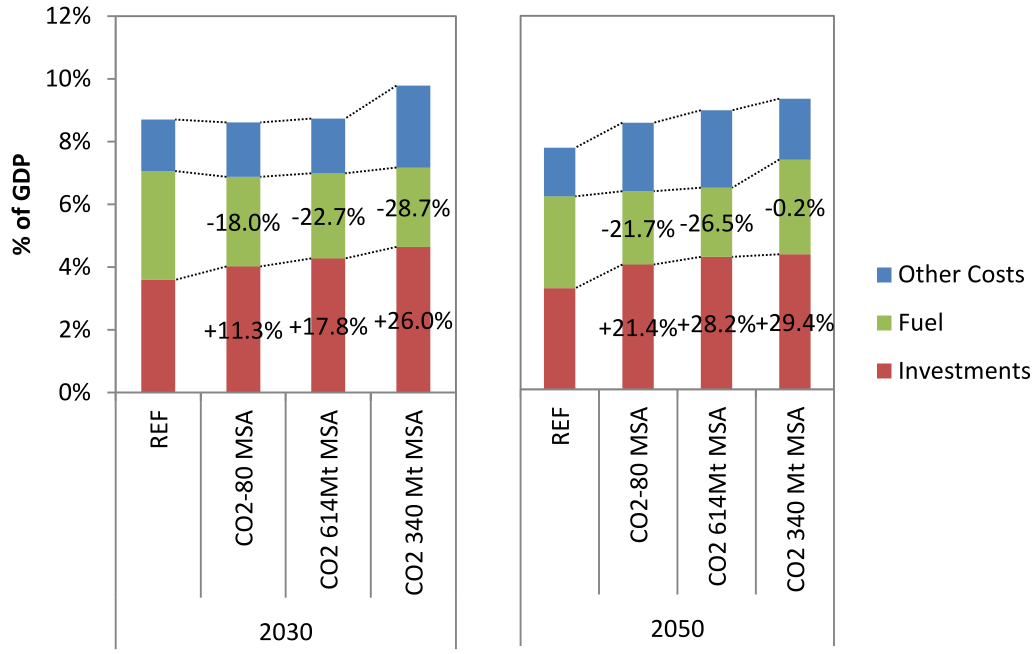


Figure 6.7 Energy system summary costs as % reference projected GDP per scenario. The labels in percentage show increases in costs relative to the reference case in absolute terms.

The summary macroeconomic consequences of decarbonising the Irish energy system are outlined below in Table 6.2. The Annualised GDP growth for the reference calibration scenario is projected at 4% between 2015 and 2020, slowing to 2.2% in 2020, and 1.2% beyond 2030 growing to €$_{2009}$339bn by 2050. The projected actual GDP, for each scenario for each period year, reflects the increasing energy costs and resultant loss in GDP. The decarbonisation scenarios GDP losses range from 0.1% to 0.8% by GDP, highlighting the low hanging fruit in energy end use efficiency, and relative negligible losses in GDP in the short term to 2020. By 2030 GDP losses range from 0.5% to 2.5% GDP, increasing with the level of ambition for decarbonisation. Final GDP loss in 2050 ranges from 1.6% in the CO2-80 scenario to 3.1% in the CO2 340Mt scenario (See Figure 6.8). The annualised effect of these GDP losses dampens GDP growth, but only slightly, slowing relative to the reference case by 10 percentage points in the short term, and by 2 percentage points in the long term. Non-energy related investment drops by 4% - 5% annually in the range of €2bn - €3bn over the model horizon. Consumption in the economy also decreases relative to the reference scenario in the range of 20 percentage points by 2020, and to -1.3% to -2.8% by 2050, increasing with decarbonisation ambition.

MACRO Calibration	2015	2020	2030	2050
GDP REF (€ Bn)	€179	€217	€267	€339
GDP REF Gr	4.0%	2.2%	1.2%	1.2%
GDP Actual				
REF (€ Bn)	€179	€217	€267	€339
CO2-80 MSA (€ Bn)	€179	€217	€265	€333
CO2 614Mt MSA (€ Bn)	€179	€216	€264	€331
CO2 340Mt MSA (€ Bn)	€179	€215	€260	€328
GDP Loss				
REF				
CO2-80 MSA		0.11%	0.49%	1.65%
CO2 614Mt MSA		0.45%	1.05%	2.21%
CO2 340Mt MSA		0.83%	2.42%	3.12%
Annualised GDP Growth Rate				
REF	3.97%	2.19%	1.21%	1.21%
CO2-80 MSA	3.94%	2.16%	1.17%	1.23%
CO2 614Mt MSA	3.87%	2.13%	1.17%	1.17%
CO2 340Mt MSA	3.79%	1.98%	1.17%	1.19%

Table 6.2 Gross Domestic Production for calibration, scenario projected GDP, scenario projected annual GDP loss, and Annualised GDP growth rates

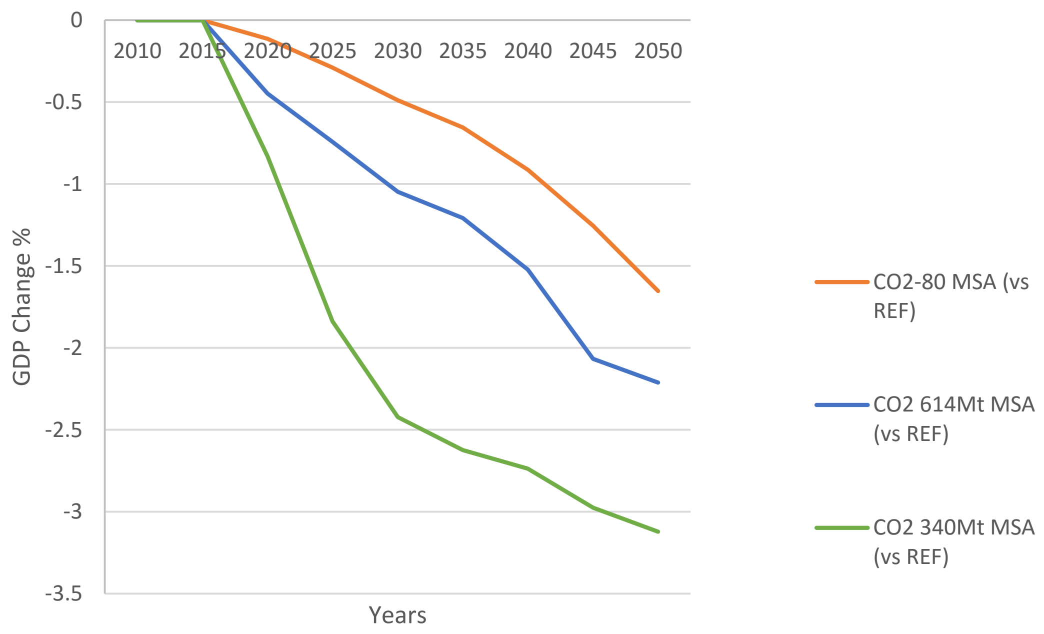


Figure 6.8 Relative GDP Change to Reference GDP projection.

6.4 Conclusions

This hybrid model approach shows that decarbonising the Irish energy system is not excessively expensive as a proportion of gross domestic production, nor is the reduction in production significant enough to pose concern for annual economic growth. Even in the case of deep decarbonisation pathways based on equity principles, with deeper faster emission reductions than EU 2050 targets, the economic impact from this analysis is not significant. It should be noted that this model does not include an economic damage function to the Irish economy and ecosystem services as a result of production changes due to climate change, nor does it include the induced competition effect due to unequal burden sharing effort over time. (Nordhaus, 2007; Stern, 2006; The Global Commission on the Economy and Climate, 2014). An economic damage function would have a positive effect on relative economic growth compared to the business as usual case, while competition effects depend on the impact on production costs from the relative rate of decarbonisation between trade partners and competitors.

The next steps in this modelling approach are to develop model linkages to a structural model of the Irish economy. This work is near completion linking Irish-TIMES to the HERMES model, and will aim in the future to develop further the fiscal and monetary model of the Irish economy COSMO[14] (Hennessy and FitzGerald, 2011).

Inclusion of an ecological economic feedback mechanism to a structural economy model including an ecosystem service damage function will give greater insight into the economic costs and benefits of decarbonising the energy system. This would enable exploration of the degree of substitutability in the Irish economy, given the lack of heavy manufacturing, lower energy demand intensity and relatively lower degree of substitutability. This model might allow exploration of capital value share of exergy services, its factor share of production, and how to endogenise population dynamics to evaluate capital-labour shares in production. Methods of calculating the consumptive and productive energy systems costs need to be quantified for targeted investment in innovation technologies.

Interesting questions for future modelling would include what is the cost of carbon that would incentivise Irish dairy farmers to switch to forestry, sequestering carbon, and receiving payment for that service? How does demand destruction affect renewable energy penetration targets?

[14] http://www.modelling-ireland.com/

Chapter 7 EQUITABLE FINANCE FOR TECHNOLOGICAL MITIGATION BELOW 2°C AND TOWARDS 1.5°C.

Primary Outputs:

Glynn, J., Kypreos, S., Lëhtila, A., Ó Gallachóir, B., 2015. Equitable finance for technological mitigation below 2°C towards 1.5°C. Nature Climate Change (Submitted)

Glynn, J., Kypreos, S., Lëhtila, A., Ó Gallachóir, B., 2015. Who pays for climate mitigation technologies? Quantifying green capital transfers for equitable decarbonisation. Presented at the 21st Conference of Parties (COP21), 30th November – 12th December 2015, Paris, France

Ó Gallachóir, B., Glynn, J. 2015. Links between energy systems models and economic models: Learning from the IEA ETSAP experience. Presented at Our common future under climate change, 7th – 10th July 2015, UNESCO, Paris, France

Kypreos, S., Glynn, J., Gargiulo, M., Lehtila, A., Ó Gallachóir, B. 2015. Modelling Efficient and Equitable Scenarios for a Carbon Constrained World with TIAM-MACRO. Presented at Our common future under climate change, 7th – 10th July 2015, UNESCO, Paris, France

Glynn, J., Kypreos, S., Lehtila, A., Gargiulo, M., Ó Gallachóir, B. 2015. Optimal Equitable Burden Sharing: Modelling global macroeconomic impacts of the carbon constrained energy system using ETSAP-TIAM-MSA. Presented at the International Energy Workshop, 3rd June 2015, Abu Dhabi, United Arab Emirates.

Glynn, J., Kypreos, S., Lehtila, A., Gargiulo, M., Ó Gallachóir, B. 2015. Modelling efficient and equitable scenarios for a stringent carbon constrained world with IEA ETSAP's Integrated Assessment Model TIAM-MACRO. Presented at the Integrated Assessment Modelling Consortium, 16th – 18th November 2015, Potsdam, Germany.

Winning, M., McGlade, C., Glynn, J. 2015. The regional macroeconomic effects of delayed action in meeting a global 2 degree climate target. Presented at Our common future under climate change, 7th – 10th July, UNESCO, Paris, France.

7.1 INTRODUCTION

Global cumulative carbon dioxide (CO_2) emissions from fossil fuel combustion and cement production (FFI) since industrialisation are estimated at 1350 $GtCO_2$ (Le Quéré et al., 2015). FFI accounts for approximately 78% of annual anthropogenic emissions. Half of all cumulative anthropogenic CO_2 emissions have occurred in the past 40 years and overall anthropogenic emission rates and carbon intensity have increased over the last decade. Increasing energy system carbon intensity between 2000-2010 has contributed to GHG growth increasing to 2.2% per year when compared with 1.3% per year over the previous three decades (Edenhofer et al., 2014). The energy system analysis of the International Energy Agency's (IEA) New Policy Scenario leaves the world on track for a long term average temperature increase of 3.6°C, dangerously beyond the 2°C limit (IPCC, 2013; OECD/IEA, 2013). A restructured low-carbon world economy is thus an imperative goal (Capros et al., 2014; Krey et al., 2014).

Given the near linear relationship between cumulative emissions and temperature rise (Allen et al., 2009; Meinshausen et al., 2009), the remaining cumulative CO_2 budgets required to stay below 2°C warming are estimated at between 1000 $GtCO_2$-1500 $GtCO_2$ (Friedlingstein et al., 2014; Pachauri et al., 2015; UNEP, 2014). Cumulative emissions vary widely on a regional and per capita basis. This study adds breadth to the burden sharing analysis being carried out running up to COP21. The LIMITS project focused on what are the feasible 2°C mitigation pathways remaining after the Durban platform (Kriegler et al., 2013) and assessed carbon permit redistribution rules to assess resource sharing and effort sharing (Kober et al., 2014; Tavoni et al., 2015, 2013). The analysis in this paper focuses on equitable burden sharing and explores cumulative historical and future emissions pathways to assess potential equitable and efficient mitigation costs. Least cost efficient emissions are compared alongside 7 burden sharing rules, including contract and convergence equalisation of emissions per capita (Bows and Anderson, 2008), equalisation of regional GDP loss, compensation for energy cost increases in Least Developed Countries (LDCs), full compensation for GDP loss in LDCs and three interpretations of the “Brazil Proposal” of historical cumulative responsibility for temperature forcing (UNFCCC, 1997). As with other studies we outline potentially equitable regional cumulative emissions budgets (Raupach et al., 2014), emission peaking dates and the distribution of energy system costs.

The novel methodological element of this work is accounting for the regional macroeconomic impacts of burden sharing rules in a post optimisation analysis (POA) of the emissions distribution of a 2°C scenario in the IEA-ETSAP’s Integrated Assessment model TIAM-MACRO. Recent additional functionality moves TIAM from a partial equilibrium (PE) to a multi-regional inter-temporal general equilibrium (GE) model (Kypreos and Lehtila, 2015). This is the first application of the new hybrid bottom-up (BU) technology-rich engineering energy systems model, hard linked to the top-down (TD) general equilibrium model (Glynn et al., 2015a, 2015b; Labriet et al., 2015). This allows the estimation of regional GDP changes as a result of trade, investment, consumption, energy costs, resultant energy service demand price adjustment, and carbon permit trade, rather than simply estimating energy system investment costs as a percentage of GDP as a proxy for macroeconomic impact.

7.2 MOTIVATION

Global coordinated action on climate mitigation has been slow (UNEP, 2014). Although a policy framework which harmonizes carbon pricing across regions that ensures economic efficiency and minimise costs would be ideal (Tavoni et al., 2013), fragmented policies and political infeasibilities make near term global carbon tax unlikely (Bertram et al., 2015). Regional differences in climate impacts, institutional capital, transaction costs, social capital and social norms make it difficult to mitigate the ongoing tragedy of the commons (Dietz et al., 2003; Hardin, 1968; Ostrom, 2000, 1990; Ostrom and Field, 1999). Alternatively, the 2030 sustainable development goals presents the global ambition to tackle the twin objectives of climate change mitigation and eradicating poverty (United Nations, 2015, 2014). In this vein of polluter pays (PPP) and equity principles, this study outlines the welfare cost differences between least cost and equitable burden sharing budgets for mitigation scenarios following cumulative CO_2 budgets for the 2°C limit, with 66% probability of success by 2100. The purpose is to inform and encourage greater binding participation in mitigation commitments by exploring differing burden sharing rules.

7.3 METHODS

The hybrid global integrated energy system model, TIAM-MACRO, is used to quantify the least cost optimal mix of low carbon technologies for a 2°C pathway, while, giving additional insight into the overall macroeconomic consequences of decarbonising the energy system. Further to estimates of the GDP loss, capital transfers from developed to developing countries are estimated to make burden sharing equitable. The seven burden sharing rules employed are outline below.

7.3.1 TIAM-MACRO

TIAM-MACRO is the hybrid TIMES Integrated Assessment Model (TIAM) developed within the Energy Technology Systems Analysis Programme (ETSAP), a global implementing agreement of the International Energy Agency (IEA) member countries. The hybrid version of the model used in this work is hard linked with a general equilibrium MACRO module (Kypreos and Lehtila, 2015; Manne and Wene, 1992; Messner and Schrattenholzer, 2000).

TIAM independently calculates a dynamic inter-temporal partial equilibrium on global energy and emissions markets based on minimisation of total discounted energy system cost with perfect foresight to 2100 (Loulou, 2008; Loulou and Labriet, 2008). The model has global coverage, with 15 regions, their resource potentials and trade connections. The model uses exogenous macroeconomic drivers to generate 45 price- elastic energy service demands across all sectors of the global economy. It has a rich technology database of over 1500 energy technologies, and their relevant commodities. TIAM encompasses a full cradle to grave representation of the energy system from resource production, refining, transport, trade, generation, consumption and sequestration of final energy commodities and the investment, operation, maintenance, and decommissioning of intermediary technologies. Energy commodities include a full spectrum of resource potentials and their costs for fossil fuels, nuclear, bioenergy, both traditional and modern renewable technologies, while endogenously accounting for three main greenhouse gases emitted: Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous dioxide (N_2O). An integrated climate module models greenhouse gas concentrations, radiative forcing and temperature changes.

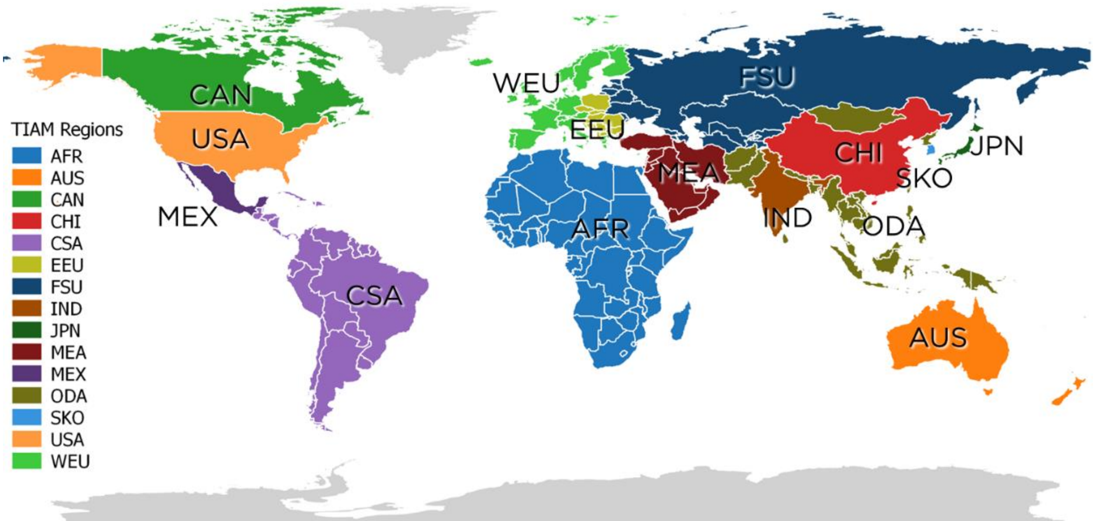


Figure 7.1 TIAM Regional divisions of the world

7.3.2 MACRO STAND ALONE – DECOMPOSING TIMES-MACRO

The additional MACRO STAND ALONE (MSA) module, developed by (Kypreos and Lehtila, 2015), allows multi-regional macroeconomic impacts to be calculated. MSA, is a multi-regional, intertemporal general equilibrium optimal growth model which maximises discounted utility of a single consumer-producer agent. The MSA module objective function supersedes the least cost minimisation objective of TIAM. GDP is comprised of consumption, investment and energy system costs. Total economic production is determined as a function of energy, capital and labour, where energy substitutes with a capital-labour composite via an elasticity of substitution. Decomposing the energy system solution into a quadratic cost function and price responsive demand, decoupling factors estimated from the calibration routine are the coupling link between TIAM and MSA. MSA solves a general equilibrium in an iterative convergent process, re-estimating price responsive energy service demands in TIAM.

7.3.3 Scenario Analysis

Two scenario types are applied in TIAM-MACRO, a counterfactual "BASE" scenario and a 2°C scenario "2DS", with 7 burden sharing rules to complete the post optimisation analysis of capital transfers. A "BASE" scenario solves for least cost predicated on available resources and technologies, technology learning under existing macroeconomic projections. The 2DS scenarios begins with the same structure as the BASE scenario, with a cumulative GHG budget of 1,855GtCO_2e applied between 2020 and 2100, in keeping with a CO_2 budget for the 2°C limit with a 66% confidence decarbonisation pathway (Friedlingstein et al., 2014; Kriegler et al., 2013). Post optimisation Analysis (POA) applies 7 different burden sharing rules to the energy system results, exploring means of equitable redistribution of the cost of our 2DS mitigation scenario. The burden sharing rules are outlined below.

7.3.4 Post Optimisation Analysis Burden Sharing Rules

The following burden sharing rules redistribute the cost of reaching an efficient least cost global energy system consistent with a 2°C world. The required inputs to the post optimisation analysis are the net CO_2 emissions, energy costs, investments, consumption, gross domestic product (GDP), and GDP loss all per region. Historic national emissions are aggregated into TIAM regions. Past and future regional median fertility UN population projections are used in both TIAM and in the POA where population projections are required.

7.3.4.1 Efficient – Least Cost Optimisation with Maximising Regional Consumption

The Efficient rule represents the constraint on the energy system, and simply specifies a cumulative emissions constraint as per the literature over all regions and time steps.

$$\sum_{r,t} E_{r,t} * nypp_t \leq RCEQ_{2°C,66\%} \;\; \forall t \in \{2020,2030,\dots,2100\}$$

Equation 1

$nypp_t$: Years per period (10)

$E_{r,t}$: Regional emissions at time t

$RCEQ_{2°C66\%,t}$:Remaining cumulative CO_2 emission quota for 2°C with 66% probability, at time t

7.3.4.2 *Rule 1 – Equalitarian contraction and convergence*

The first burden sharing rule (Rule 1) specifies a proportion of global emissions budget per time step to each region, interpolating between current emissions and a future equalisation of emissions per capita. The resultant annual emissions allowances per capita are plotted in Figure 7.2. Regions emitting more than this budget in the 2DS must purchase permits at the marginal price of CO_2.

$$\frac{E_r(t)}{E_w(t)} = \frac{T_2 - t}{T_2 - T_1} * \frac{E_r(T_1)}{E_w(T_1)} + \frac{t - T_1}{T_2 - T_1} * \frac{Pop_{r,t}}{Pop_{w,t}} \; \forall t \in \{2020{,}2030, \ldots ,2050\}$$

Equation 2

$E_r(t)$: Regional emission at time t

$E_w(t)$: World emissions at time t

$Pop_r(t)$:Regional population at time t

$Pop_w(t)$:World population at time t

T_1:Reference year for grandfathering convergence rule (2020)

T_2:Target year for grandfathering convergence rule (2050)

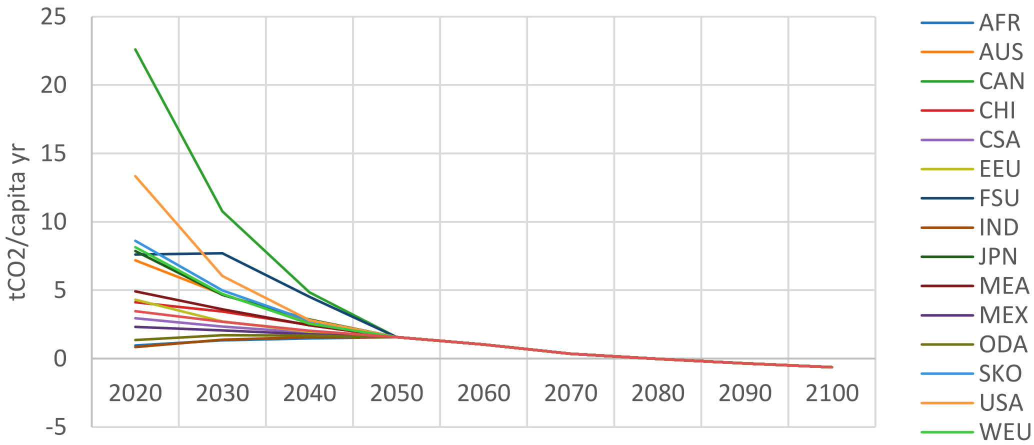


Figure 7.2 Emissions Budget Per capita rule - interpolated contraction and convergence from 2020 emission per capita to equalisation in 2050 with a grandfathering rule

7.3.4.3 *RULE 2 – GDP LOSS EQUALISATION*

Rule 2 equalises the economic impacts incurred by meeting the efficient 2DS. Regions with lesser macroeconomic impacts purchase carbon permits as a function of their relative GDP loss and of the marginal price of carbon. Regions with larger GDP impacts receive these capital transfers again as a function of their relative GDP loss above the global world rate of GDP loss.

$$\left(\frac{\Delta Y_{r,2DS}}{Y_{r,BASE}}\right)_t = \left(\frac{\Delta Y_{w,2DS}}{Y_{w,BASE}}\right)_t$$

$$\Delta Y_{r,2DS,t} \equiv \left(\frac{Y_{r,BASE}}{Y_{w,BASE}}\right)_t * \Delta Y_{w,2DS,t} = P_{w,t} * (IE_r - AE_r)_t$$

Equation 3

$\Delta Y_{r,sc,t}$: Regional GDP change per scenario at time t

$P_{w,t}$: Price of carbon dioxide (abatement) at time t

$IE_{r,t}$:Regional emissions budget at time t

$AE_{r,t}$:Actual emissions at time t

BASE:Base scenario run

2DS:2°C scenario with 66% probability

7.3.4.4 *RULE 3 – COMPENSATION FOR LDCS ENERGY COST INCREASES*

Rule 3 utilises a similar method to rule 2 with an additional constraint to subdivide regions into receiving regions and donor regions. If an LDC experiences an increase in their energy system cost (which in some time steps is not the case) relative to the base case, the LDC is compensated for that cost. The non-LDC regions pay in proportion to their ability to pay as measured by their relative GDP.

$$\sum_{rc} \Delta EC_{rc,t} \leq \sum_{rd} \Delta EC_{rc,t} * \left(\frac{Y_{rd}}{Y_{\forall rd}}\right)_t = \sum_{rd,rc} CapitalTransfer_{rc,rd,t} \leq \Delta Y_{w,t}$$

Equation 4

$EC_{rc,t}$:Developing Receiving Regions change in Energy Costs for scenario at time t

rc: Receiving regions (AFR, CSA, IND, MEX, ODA)

rd:Donor regions (AUS,CAN,CHI,EEU,FSU,JPN,MEA,SKO,USA,WEU)

Y_w:World GDP

7.3.4.5 RULE 4 – FULL COMPENSATION FOR LDCS GDP LOSSES

Rule 4, again builds on rule 3, but gives full compensation to LDCs for GDP losses as a result of the 2DS energy system costs. Again these payments are allocated on an ability to pay basis.

$$\sum_{rc} \Delta Y_{rc,t} \leq \sum_{rd} \Delta Y_{rc,t} * \left(\frac{Y_{rd}}{Y_{\forall rd}}\right)_t = \sum_{rd,rc} CapitalTransfer_{rc,rd,t} \leq \Delta Y_{w,t}$$

Equation 5

$\Delta Y_{rc,t}$:Developing Receiving Region's change in GDP at time t

rc: Receiving regions (AFR, CSA, IND, MEX, ODA)

rd:Donor regions (AUS,CAN,CHI,EEU,FSU,JON,MEA,SKO,USA,WEU)

Y_w:World GDP

7.3.4.6 RULE 5 – (BRAZIL PROPOSAL 1) REGIONAL EQUAL CARBON BUDGETS PER CAPITA WEIGHTED

The Brazilian rules below are more complicated and involved. The purpose is to balance past cumulative emissions against future emissions and equitably balance the costs. Past cumulative emissions, future cumulative emissions as per the 2DS, and equitable cumulative budgets per region and per capita are plotted in Figure 7.3.

Rule 5 allocates future emissions permits on a cumulative equal budget per population weighted region between 1750 and 2100. Regions that emit more than their allocated CO_2 budget must purchase permits from those that have not broken their budget in any given time step. Regions that have already spent their cumulative

CO_2 budget pay into a clean development mechanism (CDM), which distributes their carbon debt equally per time step as the given marginal cost of carbon at that time step.

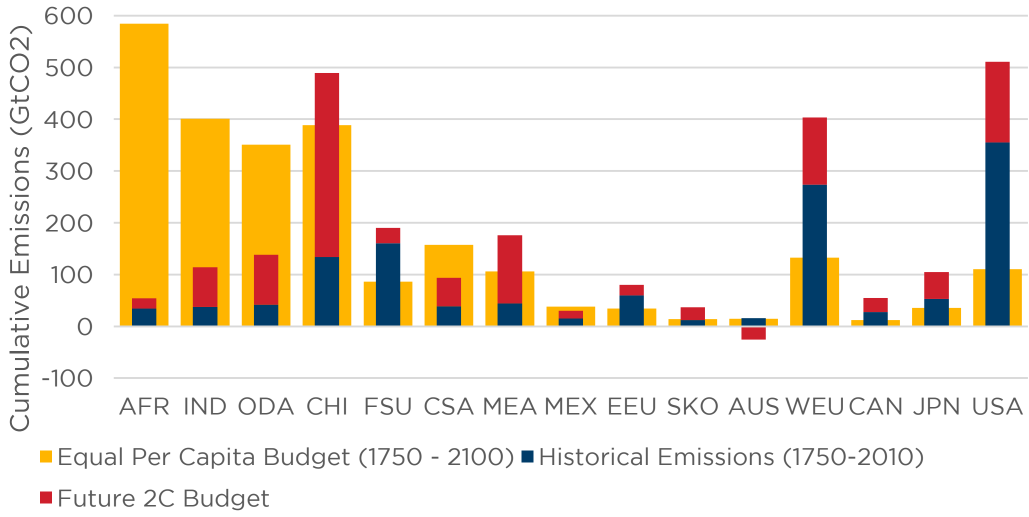


Figure 7.3 Cumulative regional CO2 emissions budgets for efficient, regional equalisation of cumulative emissions, and regional per capita equalisation of cumulative emissions (Historical Data source: Carbon Dioxide Information Analysis Center http://cdiac.ornl.gov/).

Rule 5 reallocates cumulative CO_2 budgets on a per capita basis over the past and future model horizon. This increases the number of regions that have already spent their future equitable emissions budget per capita.

$$\frac{\sum_{r,ti} AE_{r,ti} * \frac{\sum_{ti} Pop_{r,ti}}{\sum_{ti} Pop_{w,ti}} - \sum_{tj} AE_{rc,tj} - \sum_{t} AE_{rc,t}}{\sum_{rc}\left(\sum_{r,ti} AE_{r,ti} * \frac{\sum_{ti} Pop_{r,ti}}{\sum_{ti} Pop_{w,ti}} - \sum_{tj} AE_{rc,tj} - \sum_{t} AE_{rc,t}\right)} * \left(\sum_{rd} AE_{rd,t} + \sum_{rdd} CD_{rdd,t}\right) = Permit_{rc,t}$$

$$\forall ti \in \{1750, \dots, 2100\}, \forall tj \in \{1750, \dots, 2010\}, \forall t \in \{2010, \dots, 2100\}$$

Equation 6

$AE_{r,t}$: Regional emissions at time t

$CD_{rdd,t}$:Regional carbon debt exceeding projected future cumulative emissions at time t

rc: Receiving regions (AFR, AUS, CSA, IND, MEX, ODA)

rd:Donor regions (future carbon debt) (CAN, CHI, EEU, FSU, JPN, MEA, SKO, USA, WEU)

rdd:Deep Donor regions (historical carbon debt) (CAN, EEU, FSU, JPN, USA, WEU)

7.3.4.7 Rule 6 – Regional Equal Carbon Budgets Per Capita Weighted with an interim Grandfathering rule

Rule 6 is the last rule, and also interprets the Brazil proposal as a combination of an interpolation grandfathering rule from the current situation to allocation of future emissions base on population per cumulative emissions. The resultant allocation of regional emission budget per year is plotted below in

$$\frac{E_r(t)}{E_w(t)} = \frac{T_2 - t}{T_2 - T_1} * \frac{E_r(T_1)}{E_w(T_1)} + \frac{t - T_1}{T_2 - T_1} * \frac{\frac{\sum_{ti} Pop_{r,ti}}{\sum_{ti} E_{r,ti}}}{\frac{\sum_{ti} Pop_{w,ti}}{\sum_{ti} E_{w,ti}}}$$

$$\forall ti \in \{1750, \dots, 2100\}, \forall t \in \{2020, 2030, \dots, 2050\}$$

Equation 7

$E_r(t)$: Regional emission at time t

$E_w(t)$: World emissions at time t

$Pop_r(t)$:Regional population at time t

$Pop_w(t)$:World population at time t

T_1:Reference year for grandfathering convergence rule (2020)

T_2:Target year for grandfathering convergence rule (2050)

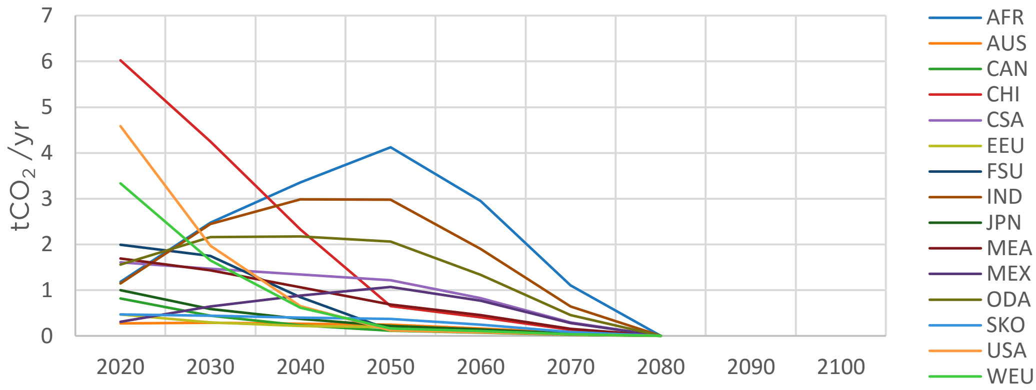


Figure 7.4 Rule 6 emissions budget per region - interpolated contraction and convergence from 2020 regional emission to weighted future emissions based on population per cumulative emissions responsibility in 2050 and beyond.

7.4 Results

The 2°C scenario (2DS) requires emission trajectories to reverse immediately with annual emission to be halved at no more than 15 $GtCO_2$/yr beyond 2050. Delayed action to 2020 makes solving for a feasible solution increasingly difficult and at a larger abatement cost, considerably so towards the end of the horizon (Kriegler et al., 2013; Tavoni et al., 2015). Significant long term growth in capacity of renewable electricity and bioenergy with CCS, combined with the removable of fossil fuels, enables the required reductions in global emissions with regional negative emissions starting in 2070, with net negative global emissions from 2080 (See the resultant energy system in Figure 7.5). The loss of productive investment capital and reductions in regional cumulative GDP are estimated between 5% and 15% depending on the effort sharing rule (Figure 7.6).

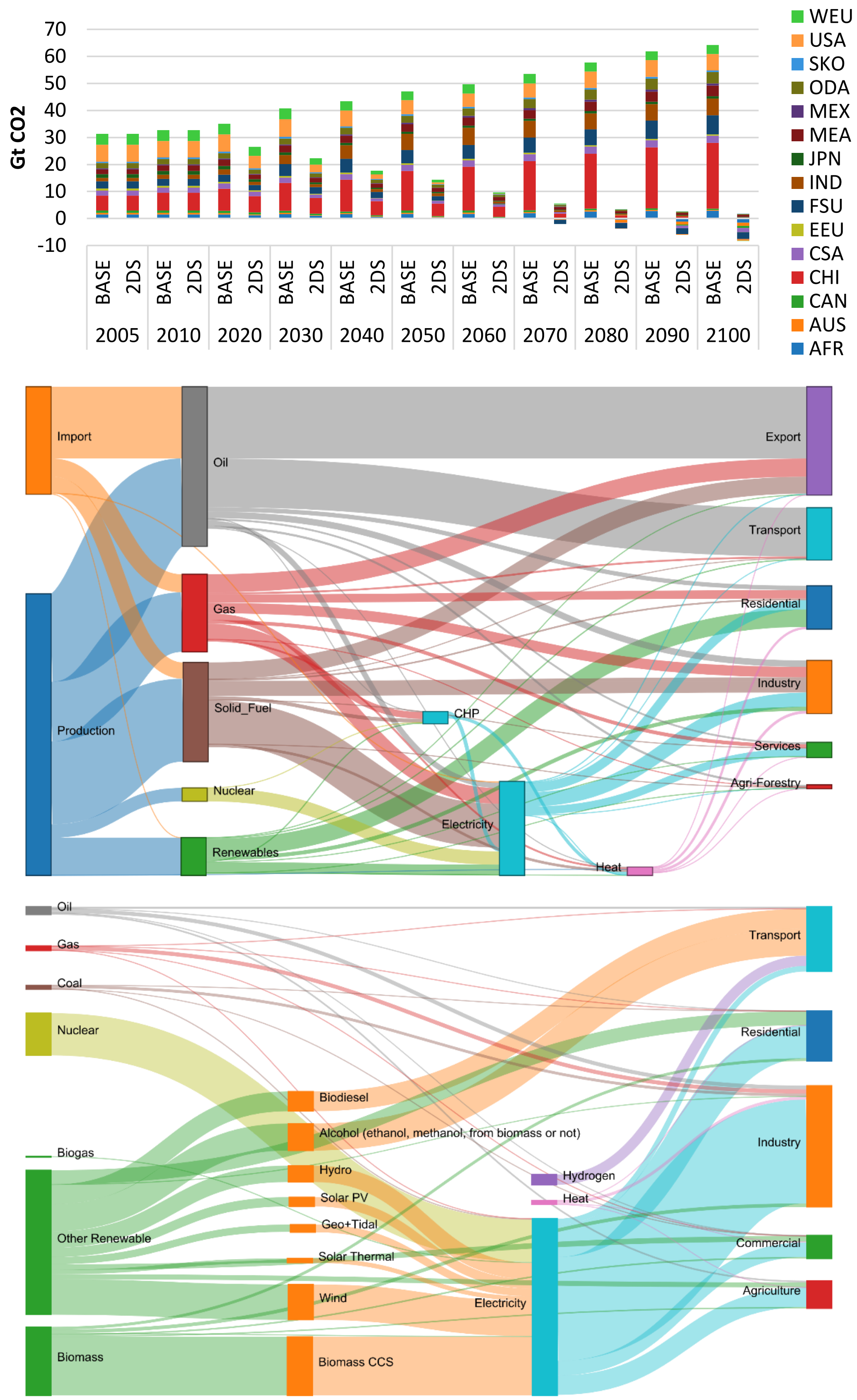


Figure 7.5 (a) Regional emissions for BASE and 2DS scenario (b) World Energy Flow 2012 (c) Final Energy for 2100 2°C mitigation scenario

While global GDP loss is in the range of 5.2% cumulatively over the model horizon, there is considerable disparity in regional GDP losses between least cost efficient, and equitable burden sharing rules (Figure 7.6). The difficulty in establishing burden sharing rules and global legislation quickly becomes both obvious and pertinent. The counterfactual BASE case economic projection does not take into account environmental damage costs to ecosystem services in the global economy due to climate change. For the least cost efficient scenario, developed service-based regions with higher GDP per capita and low energy intensity per unit of GDP output have short term economic benefits in efficiency, and, in the long term, suffer smaller cumulative losses than higher intensity newly industrialised regions. United States of America (USA), Japan (JPN), Canada (CAN), and Western Europe (WEU) have cumulative GDP losses of 2.9% - 3.3% whereas Central & South America (CSA), the Former Soviet Union (FSU), China (CHI), Other Developing Asian Countries (ODA), India (IND) and Africa (AFR) have cumulative GDP losses between 3.7% - 11.6%.

Regions with large biomass and renewable energy potentials stand to gain significantly from burden sharing rules based on emissions equalisation per capita. Ironically, given current Australian, Canadian and Former Soviet Union expansionary fossil fuel policies, their abundant renewable energy resources and low population density could more than compensate for fossil fuel revenue losses by meeting the high demand for biomass and biofuels exports, while considerably reducing the energy and carbon intensity of their domestic economies. In the long term, most of the emerging economies experience the opposite effect where GDP loss is less in the efficient scenario as opposed to the equal emissions per capita rule 1. The Middle East energy export countries suffer the largest economic losses at -17.3% cumulative GDP relative to the Baseline. China, Developing Asia and India are seen to have larger economic losses in the equal emissions per capita case (relative to the efficient case) as a result of high growth, starting from a low base of high carbon intensity energy infrastructure lock-in. Central & South America and Africa reduce their losses to near zero as a result of low energy intensity and carbon intensity per capita, starting from a low base and with slower growth than the emerging economy counterparts.

Rules 2, 3 and 4 equalise GDP losses across all regions, compensate LDCs (AFR – Africa, CSA – Central & South America, IND – India, MEX – Mexico, and ODA – Other Developing Asia) for increases in energy costs if there are any, and fully compensate the same set of LDCs for GDP losses. The redistribution of losses is seen in the central panel in Figure 7.6. High incomes countries see GDP losses rise to between 3.1% - 5.6%, LDC countries see their GDP losses drop to between 6.5% - 0%.

Rule 5, and 6 distribute emissions permits on the basis of cumulative regional and per person. Rule 5 shows USA, Japanese, Canadian and western European GDP losses rise to between 8.1% - 16%. This rule distributes historical (1750 – 2100) cumulative emissions responsibility, attributing cost to emissions, past and present. The volume of carbon permits and capital transfers per rule are plotted in Figure 7.7 and Figure 7.8.

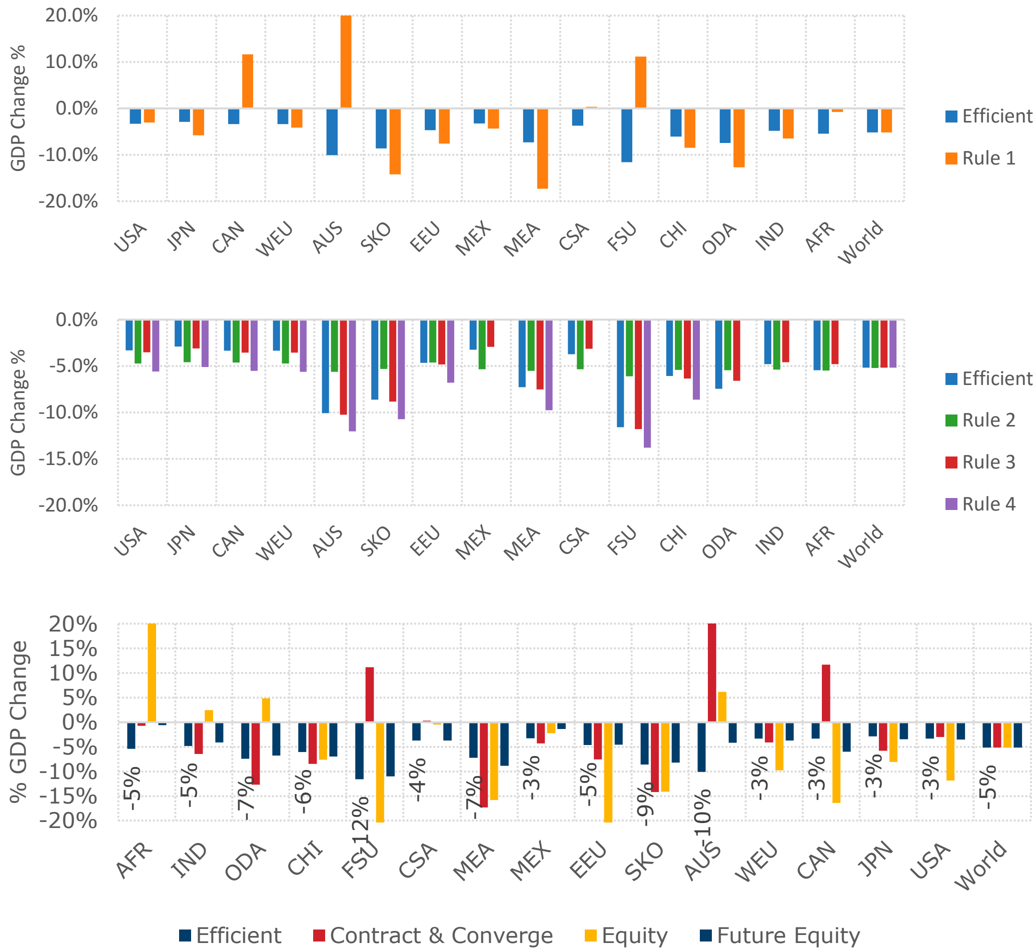


Figure 7.6 Regional Cumulative GDP change relative to the Base scenario for the EFFICIENT (EFF) 2°C 66% scenario with a global discount rate of 5%, Rule (1) Contract and Convergence to equal emissions per capita, Rule (2) Capital Transfers to Equalise regional GDP losses, Rule (3) Compensation for developing countries for increases in energy system costs if any, Rule (4) Full Compensation of GDP Loss for Non Annex 1 countries, Rule (5) "Equity" Regional allocation of cumulative population weighted cumulative emissions permits and Rule (6) "Future Equity" Brazilian rule allocation of future emissions weighted to historical population per cumulative emissions.

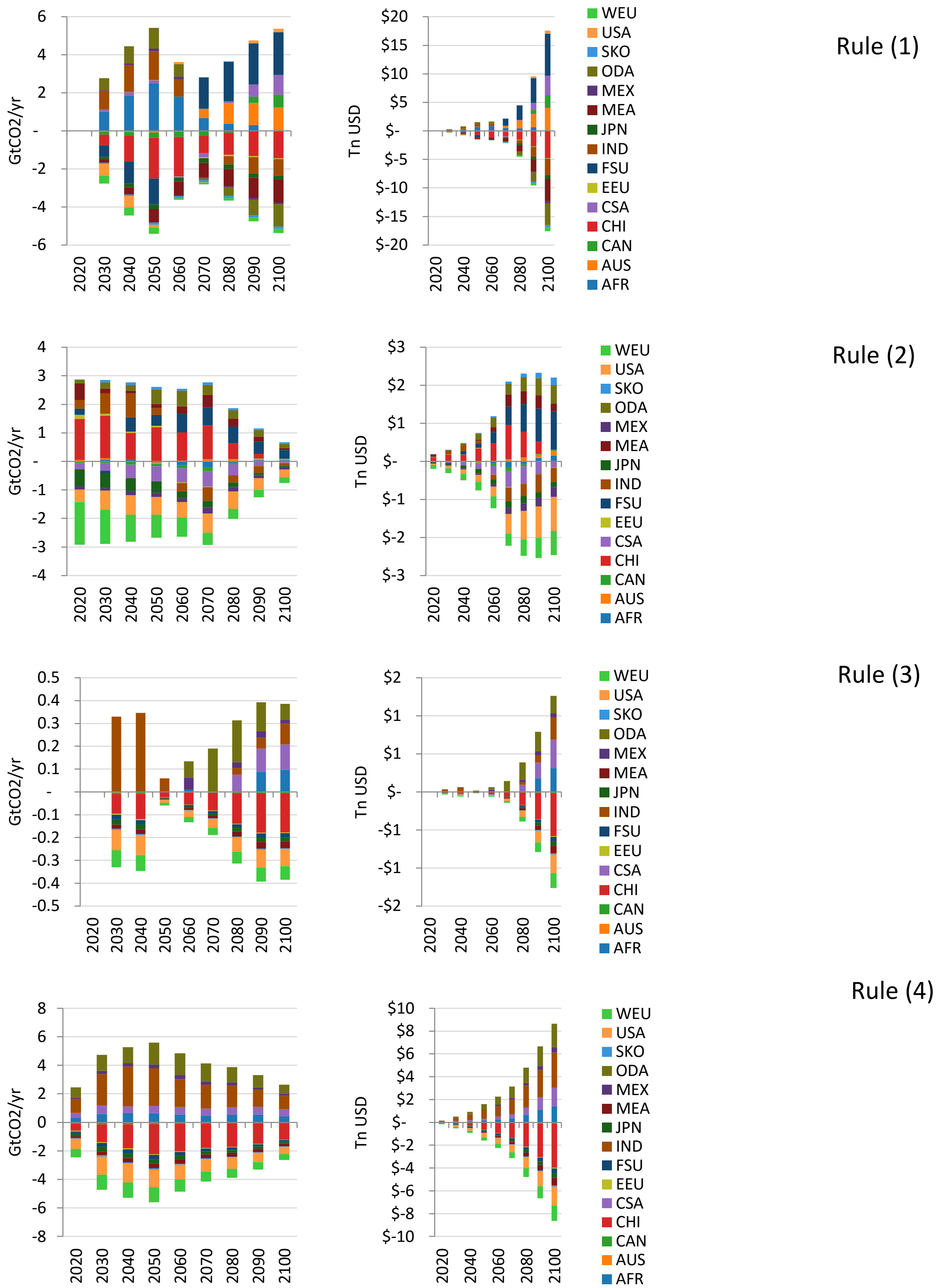


Figure 7.7 Equitable Burden Sharing rules Rule 1 – 4 (top to bottom); Carbon Permits GtCO2 (Left), Capital Transfers Tn US Dollars (Centre) per region per time period and Cumulative (2010 – 2100) GDP loss per region (Right). Rule (1) equal emissions per capita, Rule (2) Capital Transfers to Equalise regional GDP losses, Rule (3) Compensation for developing countries for increases in energy system costs if any and Rule (4) Full Compensation of GDP Loss for Non Annex 1 countries

Each burden sharing rule presents different winners and losers. Regions that may intuitively benefit in the short term, do not necessarily gain in the long term, nor cumulatively over the model horizon to 2100. Such is the case for India & China in the equal emissions per capita case: rule 1. This observation points to careful consideration of each burden sharing rule, and the consequences of the future energy system evolution. China and the Former Soviet Union benefit the most from GDP equalisation rule 2, with China receiving the majority of the permits in the short to medium term commensurate with the transformation their energy system must undergo, while the FSU receives the majority share measured in undiscounted value of permits towards the end of the century. Africa, Developing Asia and India benefit from inward investment in their energy systems from compensation rules 3 and 4. India receives the majority of the short term carbon permits from rule 3, compensating for the increases in energy system costs. The volume of permits is a factor to 10 smaller than the other burden sharing rules. However, all LDCs as a set together benefit most by full compensation of GDP losses.

However, looking further into cumulative historical responsibilities in Figure 7.8, there is a divergent result shown among LDCs, and between developed and less developed countries. Results show the African region requires the most capital transfers from either the perspective of compensating economic losses or from the historical cumulative emissions responsibility perspective. Rule 6 results show that the three least developed regions on a per capita basis currently (ODA, IND and AFR) would receive the largest capital transfers, and would return their economies to growth. The Australian – Oceania region also positively grows as result of low historical emissions per capita. The USA and WEU share the majority of the financial burden of the cumulative responsibility for Rule 5 and 6, while China is shown to take the majority of future cumulative emissions responsibility.

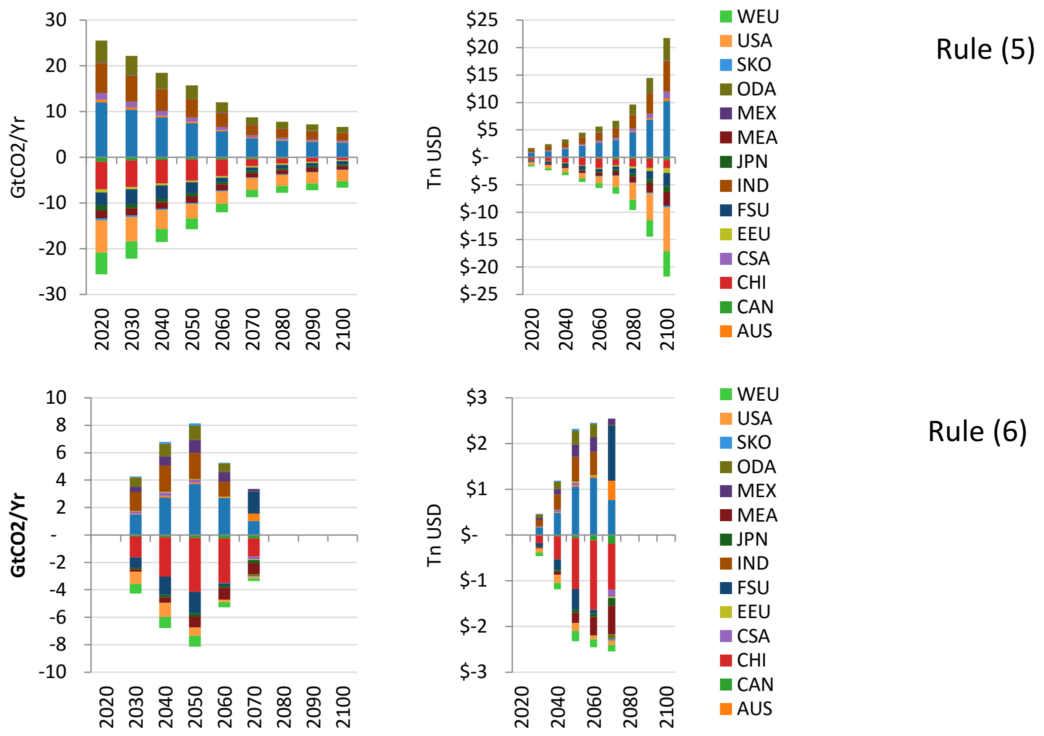


Figure 7.8 Interpretation of the Brazilian Proposal for burden sharing. Rules 5 - 6 (top to bottom); Carbon Permits GtCO2 (Left), Capital Transfers Tn US Dollars (Centre) per region per time period and Cumulative (2010 – 2100) GDP loss per region (Right)., Rule (5) Regional allocation of cumulative population weighted cumulative emissions permits and Rule (6) Brazil rule allocation weighted to population per cumulative emissions.

7.5 EQUITY "BRAZILIAN" PROPOSALS – COP21 COUNTRY LEVEL FOCUS

7.5.1 *WESTERN EUROPE*

Europe's cumulative GDP loss in the least cost 2DS solution is 3.3%. Europe has already emitted its equitable share of emissions and so trades accordingly causing GDP losses of 4% - 10% GDP depending upon the share of future emissions allowed to be emitted. Capital Transfer range from -\$1.2 Tn to -\$14.2Tn discounted at 5%, or -\$7.6 Tn to -\$134 Tn undiscounted 2020 – 2100.

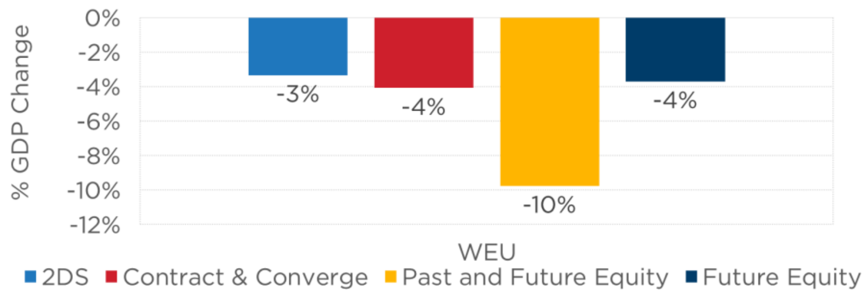


Figure 7.9 Western Europe Macroeconomic impacts from equitable decarbonisation effort sharing rules.

7.5.2 China

China's cumulative GDP loss in the least cost 2DS solution is 6.1%. The "Future Equity" effort sharing rule 6, causes relative GDP losses of 7% but less than the other effort sharing rules presented. Capital Transfer range from -$4.9 Tn to -$8.5Tn discounted at 5% or -$43 Tn to -$114 Tn undiscounted 2020 – 2100.

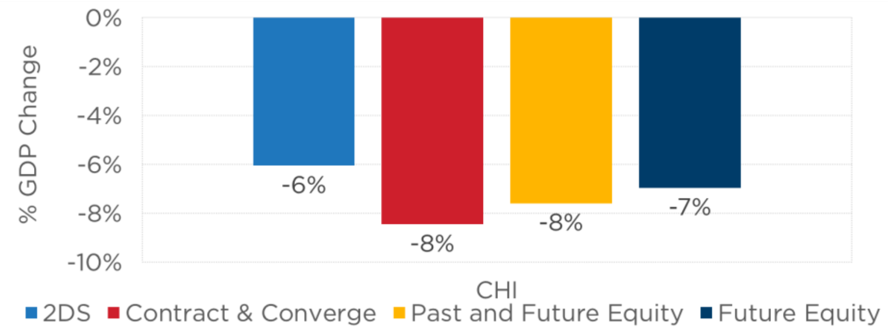


Figure 7.10 Chinese Macroeconomic impacts from equitable decarbonisation effort sharing rules.

7.5.3 India

India's cumulative GDP loss in in the least cost 2DS solution is 4.8%. Again the "Past and Future Equity" effort sharing rule 5, causes relative GDP growth of 2.5%. Capital Transfer range from +$1.7 Tn to +$16.5Tn discounted at 5% or -$38.9 Tn, to +$168 Tn undiscounted 2020 – 2100.

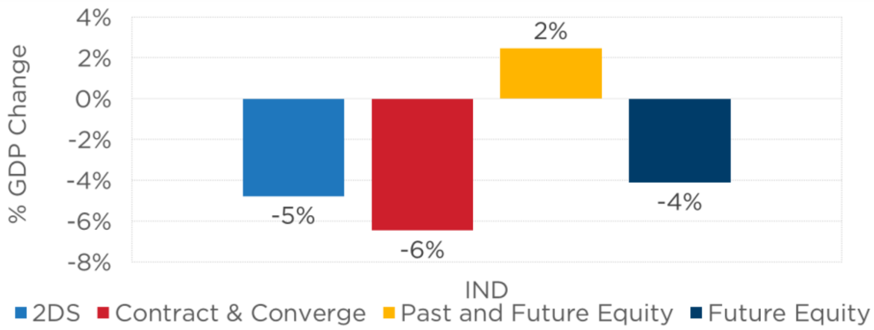


Figure 7.11 India's Macroeconomic impacts from equitable decarbonisation effort sharing rules.

7.5.4 *Africa*

Africa's cumulative GDP loss in in the least cost 2DS solution is 5.4%. The "Past and Future Equity" effort sharing rule 5, causes relative GDP growth of 34% given the continents lack of responsibility, low GDP growth, and high population growth projections. Capital Transfer range from +\$5.6 Tn to +\$30.6Tn discounted at 5%, or -\$36 Tn to +\$311 Tn undiscounted 2020 – 2100.

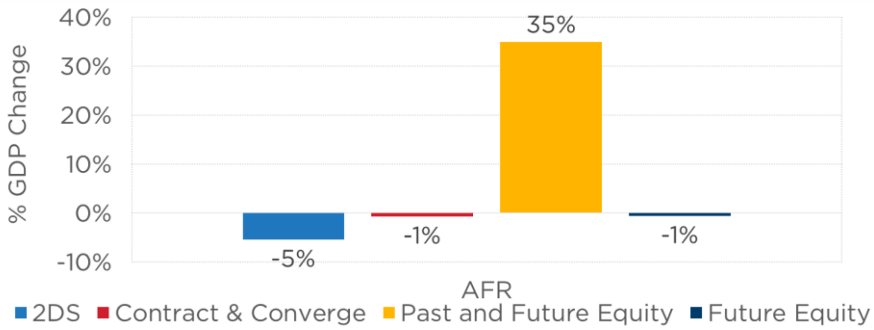


Figure 7.12 Africa's macroeconomic impacts from equitable decarbonisation effort sharing rules.

7.6 Conclusions

Hybrid integrated modelling of this nature show regional CO_2 emissions typically decline relatively in scenarios that incorporate macroeconomic feedback, (as opposed to those that do not) as a result of energy service demand adjustments and resultant energy - related emissions, as energy demand reduces with increased cost. This work displays non-linear, sectorally non-uniform demand responses that cannot be captured with typical simple demand price elasticity. The reduction in energy service demand can be in the range of between 5% and 13% by 2050, depending upon the sector and structure of the regional economy, while losses of

GDP can be in the range of 2.5% - >20%, depending on economic structure and burden sharing rules. This also reduces the modelled CO_2 abatement cost, when compared to models without macroeconomic feedback.

The Burden Sharing rule which requires the least capital transfers is that of compensation of LDC countries for energy cost increases. This rule aims to encourage investment in the most efficient mitigation pathway funded by developed regions where global cumulative GDP losses are in the region of 5.2% over the horizon.

The Brazilian Proposal interpretations, Rules 5, and 6, provide interesting perspectives for cumulative responsibility for mitigation with principles of equity and fairness in burden sharing. Looking first at rule 5, where an equal emissions budget is allocated per region over the period of 1750 to 2100 and where past emissions per country are aggregated to a regional level, and future emissions follow the efficient 2DS scenario, China, USA and Western Europe are the dominant cumulative emitters.

The USA and WEU have already emitted what would be a population weighted equal cumulative emissions share. If the USA and WEU were to trade for all their CO_2 emissions from 2020-2100 under a 2D scenario, they would still overshoot above their equitable budget allocation between 1750-2100.

In this case Canada, Eastern Europe, Former Soviet Union, and Japan join the USA and Western Europe as the set of regions that have already emitted their cumulative historical emissions budget per person. 1244 $GTCO_2$ would need to be traded in this scheme. This is by far the largest permits market envisaged by these rules, and is above the total amount of future emissions budget due to the level of cumulative emissions per capita developed regions have already over-emitted (See Figure 7.2). Africa, India and Other Developing Asia receive capital transfers in the order of Tn$64 US dollars undiscounted over the century.

Rule 6 is more palatable from the developed regions perspective, causing a rise and fall of both volume and value of carbon permit trade, peaking in 2050. The scale of the market, and the lesser potential for distortionary effects, make this rule potentially more politically feasible.

The distributional distortionary effects of the capital transfers potentially create a problem in themselves, i.e. the rule should not solely become in instrument for global income redistribution (Jacoby et al., 2008; Kober et al., 2014). Regions needing to purchase permits may want to postpone purchasing permits as long as possible.

Chapter 8 Conclusions & Future work

The energy security index results of Chapter 2 show that in the Irish case, there are energy security co-benefits in ambitious climate change mitigation policy. The relatively unambitious scenarios analysed showed increasing security as a result of fuel efficiency, fuel diversity, and increased domestic renewable energy production. The recent energy security literature struggles to formulate a unified non-biased definition of energy security. The reductionist indicator perspective does not enable the analysis of trade-offs and co-benefits within the energy system to provide resilience between energy system elements. Thus an integrated energy system assessment perspective with the goal of measuring utility and GDP impacts for energy security constraints and shocks are the recommended measurement approach.

Chapters 3 to 6 outline methodologies and benefits of hybridising techno-economic models to achieve increased realism between technological richness and general equilibrium in comparison to elastic energy service demand methods. However, there is significant room for improvement methodologically.

Chapter 7 outlines why equitable effort sharing will be critical for the successful implementation in the Paris agreement, and ratchetting of INDCs. Some future effort sharing scenarios are more equitable than others. A 2°C least cost scenario can lead to between -2.9% GDP to -11.6% GDP over the model horizon to 2100 depending up the level of development and energy export dependency of a region's economy. The three primary effort sharing rules show means of equalising macroeconomic impacts. The Contract & Convergence rule shows a range of 82% GDP growth to -17.3% GDP loss regionally. Similarly the Past and Future Equity rule shows +32.6% GDP growth to -25.5% GDP loss, while the more benign Future Equity rule shows +42% GDP growth to -85% GDP loss. The scale of capital transfers required are larger than the €100 billion pledged in Copenhagen and written in the Paris accord. Equitable burden sharing rules require high capital transfers of trillions US $ between 2020 – 2100. Contract & Convergence requires $Tn 15 ($Tn 342 - undiscounted) in capital transfers, Past and Future Equity requires $Tn 65 ($Tn 660 -

undiscounted), while Future Equity requires $Tn 17 ($Tn 78.4 - undiscounted). Equitable capital transfers do not negate the requirement to also decarbonise developed regions internal energy systems.

8.1 Recommendations

Greater structural resolution is required in computational general equilibrium models utilised in hybrid linked energy systems models, considering the radical changes to the energy system and the implied structural changes that will take place. Greater structural resolution will take into account limits of substitution in classical production function methods and demand responses in the energy system.

Climate damages, local air pollution damages and ecosystem services damages need to be included in macroeconomic feedback methods to give a more accurate and policy relevant indication of the macroeconomic consequences in decarbonising the economy.

Post the Paris agreement and under United Nations equity principles including historical responsibility, developed countries with historical responsibility and ability to mitigate need to increase their decarbonisation ambition in line with the 2°C target and to aim for a maximum 1.5°C temperature increase above industrial temperature levels. Modelling in this thesis show that the Paris Agreement target will be a difficult one to meet in a least cost manor, both globally and in Ireland.

A final recommendation to Policy makers is to assess the carbon intensity per value added in each economic sector and to aim to equalise these across sectors. This is a clearer indication of economic value in a low carbon economy that the implications of a carbon tax per sector, where loopholes and incentives may misdirect an effective decarbonisation and development of a least cost technological mitigation pathway.

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